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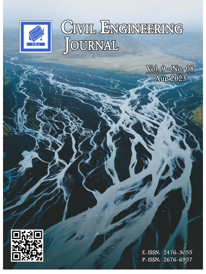

Pollution and Risk Level Assessment of Pollutants in Surface Water Bodies

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Abstract

The study was carried out to assess the pollution, impact, and risk level to the surface water environment of pollutants in the water bodies of Soc Trang province, Vietnam. The parameters for evaluating surface water quality and risks included temperature, pH, TSS, DO, BOD, COD, NH_4^+-N, NO_2^--N, NO_3^--N, PO_4^{3-}-P, Cl^-, Fe_t, and coliform. Surface water samples were collected at 35 locations with a frequency of six times (February, April, June, August, October, and December) in 2022. The water quality index (WQI), impact and risk level (risk quotient or RQ, RQ-F), correlation analysis, and principal component analysis (PCA) were utilized in the study. The results show that the surface water has been seriously polluted due to organic matter, nutrients, microorganisms, iron, and salinity. The values of WQI in the dry and rainy seasons fluctuated between bad and very good, indicating that surface water quality is suitable for water transport and other purposes with higher quality requirements. TSS, COD, Fe_t and coliform have a high impact and risk for the environment in this study area. There were no environmental impacts and risks to NO_3^--N. Locations with many high-risk pollutants were mainly distributed in residential and coastal areas. The significant negative correlation between the WQI and RQ indicated that the lower the WQI, the higher the environmental risk. The PCA results show that at least six polluting sources affected water quality and caused environmental risks. The results of this study contribute essential and valuable information for improving water quality in the study area through the assessment of environmental impacts and risks.

Keywords: Organic Matters; Risk Level Assessment; Soc Trang Province; Pollutants; Surface Water Bodies.

1. Introduction

Soc Trang is a coastal province located at the end of the Hau River with a 72 km long coastline. In Soc Trang province, the water supply for both domestic purposes and agricultural and industrial production mainly relies on surface water. Therefore, saltwater intrusion is very complicated, especially in the dry season. Moreover, consuming contaminated water can cause infectious diseases such as cholera and typhoid fever, and other diseases such as gastritis, vomiting, and skin and kidney problems [1]. Besides, using poor-quality water for irrigation will destroy crops and affect yield [2]. Therefore, the need for better management of surface water quality in the water bodies of Soc Trang province becomes necessary.

Consequently, the monitoring system is also interested and invested by many localities to improve water quality. Parameters and frequency of monitoring are increasing; typically, surface water quality is often characterized by pH, TSS, DO, organic matters (BOD and COD), nutrients (NH_4^+-N, NO_3^--N, and PO_4^{3-}-P), microorganisms, heavy metals (As, Cd, and Pb), and pesticide compounds (glyphosate, thiamethoxam, and carbosulfan) [3–5]. Therefore, the raw data on water quality is enormous. In Vietnam, the water quality index (WQI) is considered a useful and widely used tool in the environmental monitoring program to optimize monitoring data. The WQI index is calculated according to a

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mathematical formula that gathers many typical environmental parameters and represents a single number, allowing one to determine the environmental quality in a specific space and the suitability of the environment for each water use purpose [6–8]. Even so, the presence of pollutants in water can also harm water users and aquatic organisms [9, 10]. Therefore, many previous studies have used environmental risk assessment as a tool for water management because it can predict potential environmental risks from different pollutants [10, 11].

According to Zhou et al. (2019) [12], measured environmental concentrations (MECs) combined with predicted no-effect concentrations (PNECs) are commonly used to screen compounds with potential environmental risks. If some parameters exceed optimal levels or reach harmful limits, it will affect the habitat and development of aquatic species [13, 14]. Pollutants have become a threat to mollusks, fish, crustaceans, and other species [1]. For instance, high levels of total suspended solids negatively impact fish and invertebrates by clogging spawning habitats [15]. The constant increase in BOD and COD depletes the oxygen content of the water, which in turn can suffocate and kill fish and other aquatic life [15]. Nevertheless, the Mekong Delta region has limited information on the environmental risk of pollutants. Therefore, the present study addresses the research gap in the Mekong Delta. This study was implemented with three main objectives: (1) to assess surface water quality status; (2) to determine the level of impact and risk of pollutants and their distribution in the water bodies; and (3) to identify sources of impacts and risks. Based on the pollution and risk assessment results, local authorities could make decisions and develop strategies for surface water quality and risk management.

2. Research Methodology

2.1. Study Area

Soc Trang is a coastal delta province located in the southeast of the Mekong Delta, with coordinates of 9°12'-9°56' north latitude and 105°33'-106°23' east longitude, bordering Hau Giang province in the north and Northwest, bordering Bac Lieu in the Southwest, Tra Vinh in the East and the East Sea in the South. The total natural land area of the province is about 322,330.36 hectares, and the population is 1,406,800 people. The network of rivers and canals in the area is dense and evenly distributed throughout the province. At the same time, Soc Trang province has 72 km of coastline with two large estuaries: the Hau River (which flows into two large rivers) and the My Thanh River. The province's surface water is mainly exploited for agricultural production, aquaculture, industry, and domestic water supply. However, the province has a relatively low topography, heavily dissected by rivers, canals, and irrigation canals, so it is susceptible to seawater intrusion. In particular, the status of pollutant discharge streams from agricultural, industrial, and domestic activities has seriously affected surface water quality in this area.

2.2. Data Collection

In this study, the locations of surface water monitoring stations represent the areas affected by urban activities, agricultural production, industrial production, and the area bordering neighboring provinces. There are 35 surface water monitoring stations established in Soc Trang province, as detailed in Figure 1. Surface water sampling was conducted seasonally, including the dry season (February, April, and December) and the rainy season (June, August, and October) in 2022. A total of 210 surface water samples were collected at a depth of no more than 30 cm. After being collected, each surface water sample was analyzed for 13 physical, chemical, and biological environmental parameters. The key parameters were chosen according to the geographic location and surface water regulations in Vietnam. Furthermore, these parameters were also applied to some monitoring systems in other coastal provinces. In which the pH, temperature, and dissolved oxygen (DO) of each water sample were measured directly in the field. Other parameters, including total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N), orthophosphate (PO_4^{3-}-P), chloride (Cl^-), total iron (Fe_t) and coliform, were analyzed in the laboratory of the Center of Natural Resources and Environment Monitoring Soc Trang province using standard methods [16].

2.3. Data Processing

2.3.1. Water Quality Index

The Water Quality Index (WQI) is widely used to assess and classify surface water quality. It is aggregated from many environmental parameters and expressed as a single value. In Vietnam, the WQI index is proposed by the Vietnam Environment Administration, and when calculating the WQI index, at least 3 groups of parameters are required for the monitoring environment [17]. In this study, 10 surface water quality parameters, including pH, temperature, DO, BOD, COD, NH_4^+-N, NO_2^--N, NO_3^--N, PO_4^{3-}-P, and coliform, were used to calculate the WQI index at 35 monitoring locations during the dry and rainy seasons. The formula to calculate the WQI index is Equation 1:

$$\mathrm{WQI} = \frac{\mathrm{WQI_I}}{100} \times [(\frac{1}{k}\sum_{i=1}^{k} \mathrm{WQI_{II}})^2 \times \frac{1}{l}\sum_{i=1}^{l} \mathrm{WQI_{III}}]^{1/3} \tag{1}$$

Where: WQI_I is the WQI value of the pH parameter, WQI_{II} is the WQI value for chemical variables (DO, BOD, COD, NH_4^+-N, NO_2^--N, NO_3^--N and PO_4^{3-}-P), and WQI_{III} is the WQI value for the biological variable (coliform). The scale of assessing surface water quality through the WQI index is divided into 6 levels, including (1) "Very heavily polluted" when WQI < 10, (2) "Poor" when WQI = 10-25, (3) "Bad" at WQI = 26-50, (4) "Medium" at WQI = 51-75, (5) "Good" at WQI = 76-90 and (6) "Very good" at WQI = 91-100 [17]. At the same time, the RBG colour visually represents surface water quality at each monitoring location on the spatial map [17]. WQI index map was produced using QGIS software version 3.28.

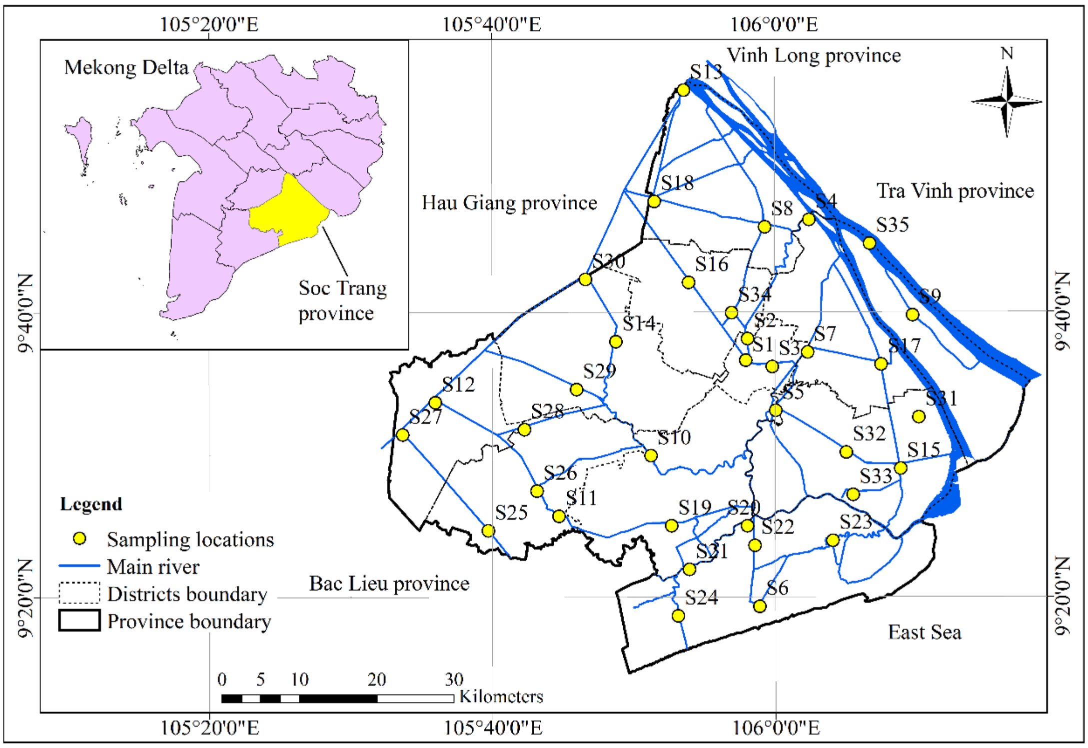


Figure 1. Location of surface water monitoring stations in Soc Trang Province in 2022

2.3.2. Risk Assessment

Environmental risks are often rapidly assessed using a risk quotient (RQ) and frequency of occurrence. RQ is calculated as the ratio between measured environmental concentrations (MECs) and concentrations predicted for no effect (PNEC), which is described as Equation 2 [18]. This study assessed the risks of 10 surface water pollution parameters, including TSS, BOD, COD, NH_4^+-N, NO_2^--N, NO_3^--N, PO_4^{3-}-P, Cl^-, Fe_t and coliform.

$$\text{Risk Quotient (RQ)} = \frac{\text{Measured environmental concentration (MEC)}}{\text{Predicted no}-\text{effect concentration (PNEC)}} \tag{2}$$

In which PNEC is the limit value of surface water quality parameters regulated by MoNRE (2015) to ensure the life of aquatic organisms are 20 mg/L, 4 mg/L, 10 mg/L, 0.3 mg/L, 0.05 mg/L, 2 mg/L, 0.1 mg/L, 250 mg/L, 0.5 mg/L and 2500 MPN/100mL, respectively [19]. MEC is the concentration of pollutants measured at 35 monitoring stations in the dry and rainy seasons. The RQ index rating scale is divided into four levels, including (1) if RQ is lower than 1, no risk is expected, (2) RQ ranges from 1 to 2, low impact is expected; RQ is between 2 and 3, moderate impact is expected and (3) $RQ \geq 3$, the impact is high [20]. Furthermore, the frequency of effects (F) is recorded based on the number of times it exceeds the limit value specified by Ministry of Natural Resources and Environment (MoNRE) (2015) [19]. In which $F > 70\%$ is assessed frequently, F range from 30 - 70% is moderate and $F < 30\%$ is infrequent [20]. Finally, the risk classification of pollutants is carried out based on the matrix between RQ and F with 4 levels (Table 1).

Table 1. Risk matrix approach for pollutants in water bodies

	Impact			
Frequency	**None ($RQ \leq 1$)**	**Low ($1 < RQ < 2$)**	**Moderate ($2 \leq RQ < 3$)**	**High ($RQ \geq 3$)**
Frequent ($F > 70\%$)	Safe	Moderate	High	High
Moderate ($30\% < F < 70\%$)	Safe	Low	Moderate	High
Infrequent ($< 30\%$)	Safe	Low	Low	Moderate

2.3.3. Pearson Correlation Analysis

Pearson correlation analysis was applied to find the relationship between WQI and RQ. When the correlation coefficient between variables close to 1 shows a strong positive correlation, the variable correlation coefficient close to -1 shows a robust negative correlation [21]. Values close to 0 show no significant linear relationship. In this study, SPSS software version 20.0 was applied to Pearson correlation analysis for WQI and RQ values of all parameters used in calculating RQ at 35 sites in the dry and rainy seasons.

2.3.4. Principal Component Analysis

Principal component analysis (PCA) allows for the reduction of the original data set and forms new factors, mainly used to extract vital environmental variables and identify possible sources of surface water quality pollution [22, 23]. The Kaiser-Meyer-Olkin (KMO) and Bartlett tests were used to assess the fit of the PCA analysis dataset [16, 24]. In PCA analysis, the eigenvalue is often used to identify principal critical components (PCs). PCs with eigenvalues greater than 1 are retained to assess surface water quality variability [22, 24, 25]. The loading factor between the environmental variables and the main component is divided into three levels: strong (>0.75), moderate (0.75-0.50), and weak (0.50-0.30). [26]. In this study, the purpose of the PCA analysis was to identify the main surface water quality variables affecting surface water quality during the dry and rainy seasons. This study used the average values of 13 surface water quality parameters at 35 monitoring stations in the dry and rainy seasons for PCA analysis using SPSS software version 20.0. The research methodology is presented in a flowchart (Figure 2).

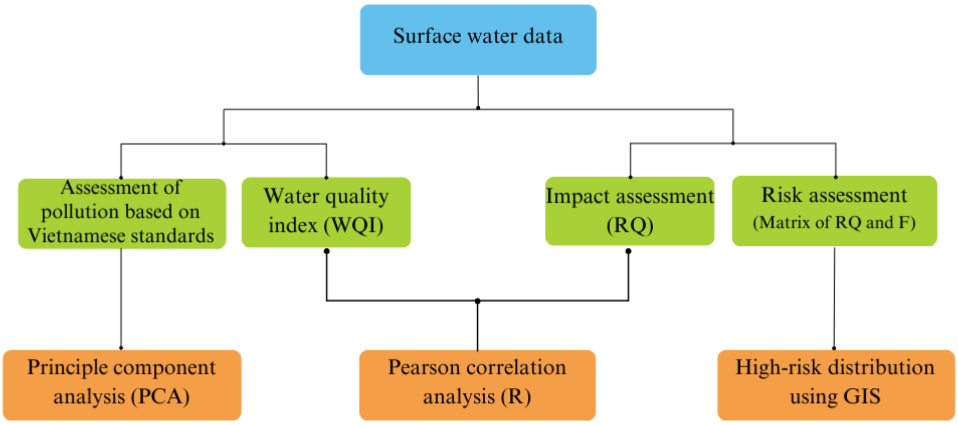


Figure 2. The flowchart of the research methodology

3. Results and Discussion

3.1. Surface Water Quality Based on National Surface Water Quality Standards

The results of Table 2 show that only temperature, pH, and NO_3^--N in surface water in the study area were within the allowable limits of national technical regulations on surface water quality [19]. Surface water in the study area has been contaminated with suspended solids, organic matter, eutrophication, salinity, iron, and microbial contamination. pH, BOD, NH_4^+-N, PO_4^{3-}-P, and Fe_t in the water had statistically significant differences between the dry and rainy seasons ($p<0.05$).

Table 2. Summary of surface water quality

No.	Parameter	Unit	Dry season	Rainy season	Min	Max	QCVN 08 MT:2015/BTNMT, A1
1	pH	-	7.05 ± 0.24^a	6.93 ± 0.21^b	6.69	7.35	6-8.5
2	Temp.	°C	30.24 ± 1.07^a	30.43 ± 1.27^a	29.27	31.70	-
3	TSS	mg/L	93.01 ± 90.21^a	92.97 ± 68.30^a	23.73	240.17	20
4	DO	mg/L	2.79 ± 0.33^a	2.72 ± 0.37^a	2.22	3.49	6
5	BOD	mg/L	4.5 ± 2.05^b	4.74 ± 1.2^a	2.58	6.88	4
6	COD	mg/L	31.39 ± 12.62^a	30.29 ± 11.09^a	11.02	47.20	10
7	NH_4^+-N	mg/L	0.44 ± 0.5^b	0.58 ± 0.56^a	0.03	2.21	0.3
8	NO_2^--N	mg/L	0.06 ± 0.11^a	0.06 ± 0.07^a	0.01	0.39	0.05
9	NO_3^--N	mg/L	0.27 ± 0.2^a	0.26 ± 0.14^a	0.10	0.54	2
10	PO_4^{3-}-P	mg/L	0.12 ± 0.42^b	0.16 ± 0.34^a	0.02	1.56	0.1
11	Cl^-	mg/L	651.19 ± 1291.33^a	286.11 ± 498.83^a	18.86	3894.03	250
12	Fe_t	mg/L	2.32 ± 1.79^b	2.62 ± 1.55^a	0.81	5.37	0.5
13	Coliform	MPN/100mL	$24{,}497\pm49{,}896^a$	$18{,}159\pm20{,}639^a$	1,687	160,333	2500

Note: ^{a}, ^{b} in the same row, the difference is not statistically significant ($p>0.05$) and vice versa.

TSS fluctuated from 93.01±90.21 mg/L (dry season) to 92.97±68.30 mg/L (rainy season), an average of 4.64–4.65 times higher than the standard. This result is similar to the previous study by Giao and Ly (2023) [27] in the surface water of Soc Trang province in 2021, exceeding 1.05–6.52 times. From that, it can be seen that the TSS content in the water in 2022 tended to increase, higher than the previous year. However, high TSS was still detected as lower than other coastal water bodies such as Ca Mau province [3, 28] and Tra Vinh province [29]. Meanwhile, TSS concentration tends to be higher than in areas with water bodies not adjacent to the sea, such as An Giang province (53.33±3.59-59.59±8.82 mg/L) [30]. High-suspended solids in water are often associated with organic or inorganic contamination; moreover, they can be carriers of microbial contamination [31].

DO in the water bodies of Soc Trang province is very low, ranging from 2.79±0.33 mg/L (dry season) to 2.72±0.37 mg/L (rainy season). The low amount of oxygen in the water seriously affects the growth and development of aquatic species. The concentrations of BOD and COD in surface water in the study area ranged from 4.5±2.05-4.74±1.2 mg/L and 30.29±11.09-31.39±12.62 mg/L, respectively. The average seasonal variation of BOD and COD content has exceeded 1.1–1.2 times and 3.0–3.1 times compared with Vietnam standards, respectively. Lower BOD and COD concentrations were recorded compared to Ca Mau province [3, 28] and An Giang province [30]. In addition, the BOD content exceeded the regulatory limit insignificantly. Meanwhile, COD content is three times higher than the allowable limit in both rainy and dry seasons. This may be due to the fact that domestic waste contains many substances that are difficult to biodegrade and industrial activities have increased COD content in water [26, 32].

For the nutrients, NH_4^+-N fluctuated from 0.44±0.5 mg/L in the dry season to 0.58±0.56 mg/L in the rainy season, averaging about 1.5-1.9 times higher than the allowable limit. The high concentration of NH_4^+-N in surface water has been recorded in most provinces or cities in the Mekong Delta and worldwide [4, 5, 30]. However, there is no significant difference between provinces in the Mekong Delta province [4, 28, 30]. This is explained by the fact that NH_4^+-N concentrations are commonly highly concentrated in areas receiving large amounts of wastewater from aquaculture, domestic, industrial and rice cultivation. NO_2^--N in the water bodies of Soc Trang province was 1.2 times higher than the allowable limit of QCVN 08-MT:2015/BTNMT [19]. Compared with some other studies, the NO_2^--N content in this study was relatively higher in Mekong Delta, namely Ca Mau province [4] and An Giang province [33]. This result is consistent with the measurement results of DO in water because the lack of oxygen in the water leads to incomplete nitrification. Consequently, the NO_2^--N concentration in the water body increases [31]. Moreover, high nitrite levels in water depend on agricultural fertilizer use and untreated wastewater discharge [8]. Organisms living in nitrite-contaminated aquatic environments can experience oxidative stress in gills and serum, negatively affecting the growth and development of aquatic organisms [34]. On the other hand, PO_4^{3-}-P in the water bodies of Soc Trang province fluctuated from 0.12±0.42 mg/L (dry season) to 0.16±0.34 mg/L (rainy season), 1.2-1.6 times higher than the Vietnamese standard. NH_4^+-N and PO_4^{3-}-P were significantly higher in the rainy season than in the dry season ($p<0.05$); the cause may be the rainy season; the overflowing rainwater brought pollutants into receiving water. This result is similar to the study of Jayasiri et al. (2022) [4] in Ca Mau province. High concentrations of PO_4^{3-}-P in water can be caused by runoff in agriculture, domestic and industrial wastewater, especially detergents [33, 35].

The concentrations of Cl^- in the dry season and rainy seasons were recorded at 651.19±1291.33 mg/L and 286.11±498.83 mg/L, respectively. These results illustrated that Cl^- was 21.87 times higher in the dry season compared to the QCVN 08-MT:2015/BTNMT [19]. Meanwhile, the concentration of Cl^- in the water in the rainy season was only 10 times higher than the standard. Fe_t concentration in the water exceeded the allowable limit of 4.5-5 times due to acid sulfate soil affecting water quality and the impact of untreated wastewater. Besides that, the previous study by Wehrheim et al. (2023) [31] suggested that the increase of Fe in water is also affected by aquaculture. Iron-rich water can cause odor and taste problems and make the water corrosive [36]. The study results showed that coliform density fluctuated in the range of 18,158±20,639-24,497±49,896 MPN/100 mL, with an average of around 7-10 times higher than the standard. The activities of discharging wastewater from livestock, aquaculture and septic tanks of poor quality have seriously contaminated the water in this area with microorganisms. Coliform contamination in water bodies is widespread in the Mekong Delta [30, 35, 37].

3.2. Overall Surface Water Quality in the Study Area

WQI values in the dry and rainy seasons are presented in Figure 3. In the dry season, WQI index values range from 26-91, dividing surface water quality into four quality levels: very good, good, medium and bad. Only one site (S35) has very good water quality, accounting for 2.86% of the total samples. Good water quality was determined at 5 locations, including S4, S8, S13, S23 and S24 (accounting for 14.29% of the total samples). The medium water quality accounted for 22.86% of the total samples found at locations S7, S10, S19-S20, S22, S25 and S28-S29. Bad water quality accounted for 60% of total samples, including positions S1-S3, S5, S6, S9, S11-S12, S14-S18, S21, S26-S27 and S30-S34. During the rainy season, WQI values fluctuated between 31 and 88, classifying surface water quality into three levels good, medium and bad. Sites with good water quality accounted for 17.14% of the total sample, including sites S4, S8, S13, S18, S21 and S35. Locations with medium water quality accounted for 20% of the total samples, including S10, S19, S23, S26, S29, S33 and S34. About 63% of the total samples (22 locations) had bad water quality during the rainy season, including S1-S3, S5-S7, S9, S11-S12, S14-S17, S20, S22, S24-S25, S27-S28 and S30-S32. Compared with the study of Le et al. (2022) [28], the WQI in Ca Mau shows that water quality is heavily polluted and poor. This indicates that the WQI shows better water quality in Soc Trang province than in Ca Mau province. However, the WQI index in Soc Trang has a similar trend with Bac Lieu province [38], which is adjacent to the southwest.

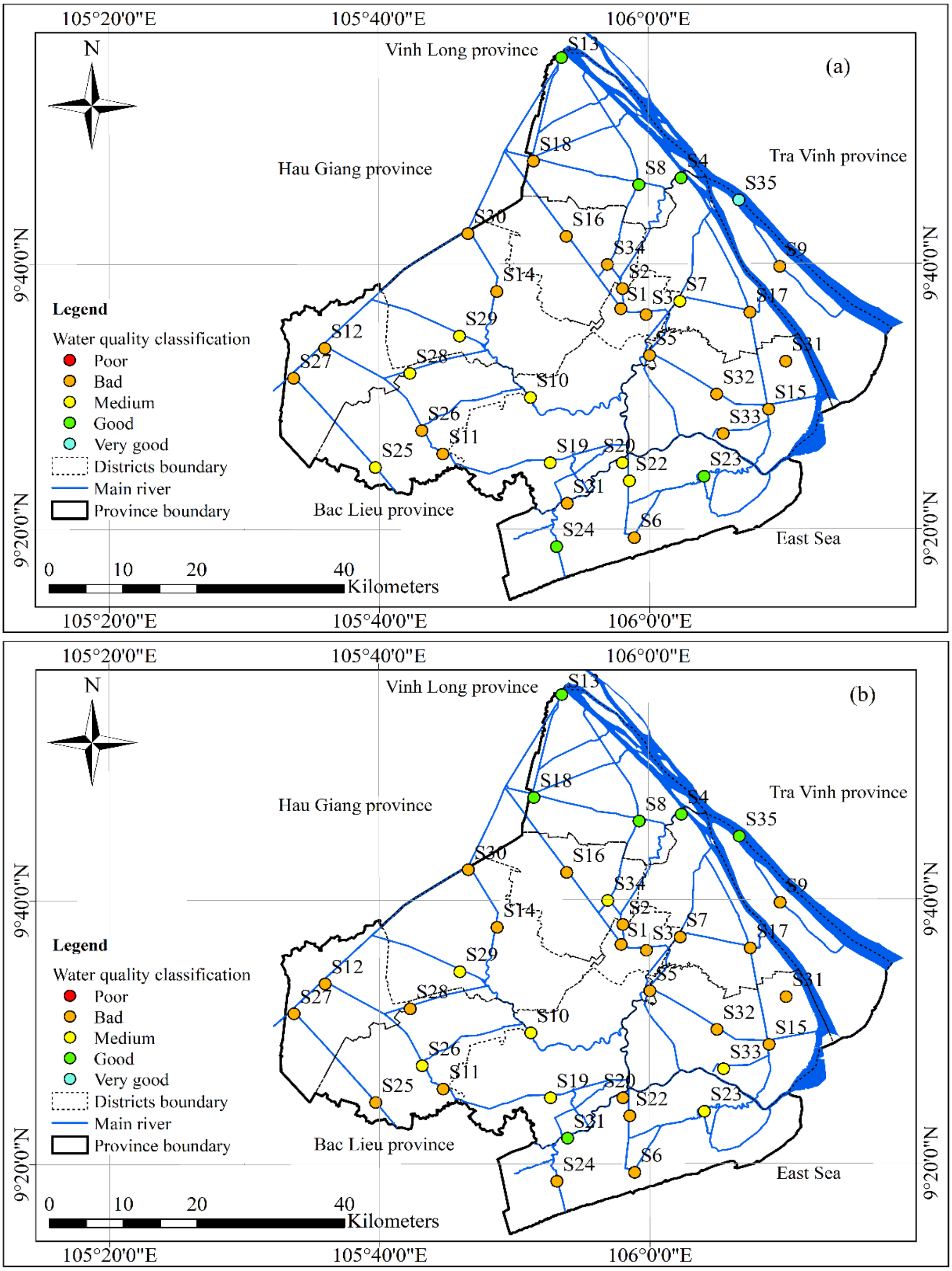


Figure 3. Distributions of WQI in (a) dry season and (b) rainy season

3.3. Risk Assessment of Pollutants

The results of the impact level (RQ) and risk level ratio in the dry and rainy seasons are shown in Table 3. TSS, COD, Fe_t and coliform parameters in the dry season were determined to have a high impact, with mean RQ values of 4.65, 3.14, 4.64 and 9.08, respectively. Furthermore, these parameters have medium and high-risk levels above 90% of the total sampling locations. Then there is Cl^-, which is recorded with an RQ value of 2.60, assessed as having a moderate impact. However, the level of risk to the environment is only low (28.6%) and safe (37.1%) because the frequency of pollution in the dry season months is less than 30%. Next, BOD (RQ = 1.12), NH_4^+-N (RQ = 1.48), NO_2^--N (RQ = 1.27) and PO_4^{3-}-P (RQ = 1.28) have environmental impacts and risks at low levels. Meanwhile, the impact and risks of NO_3^--N on the water environment were not recorded.

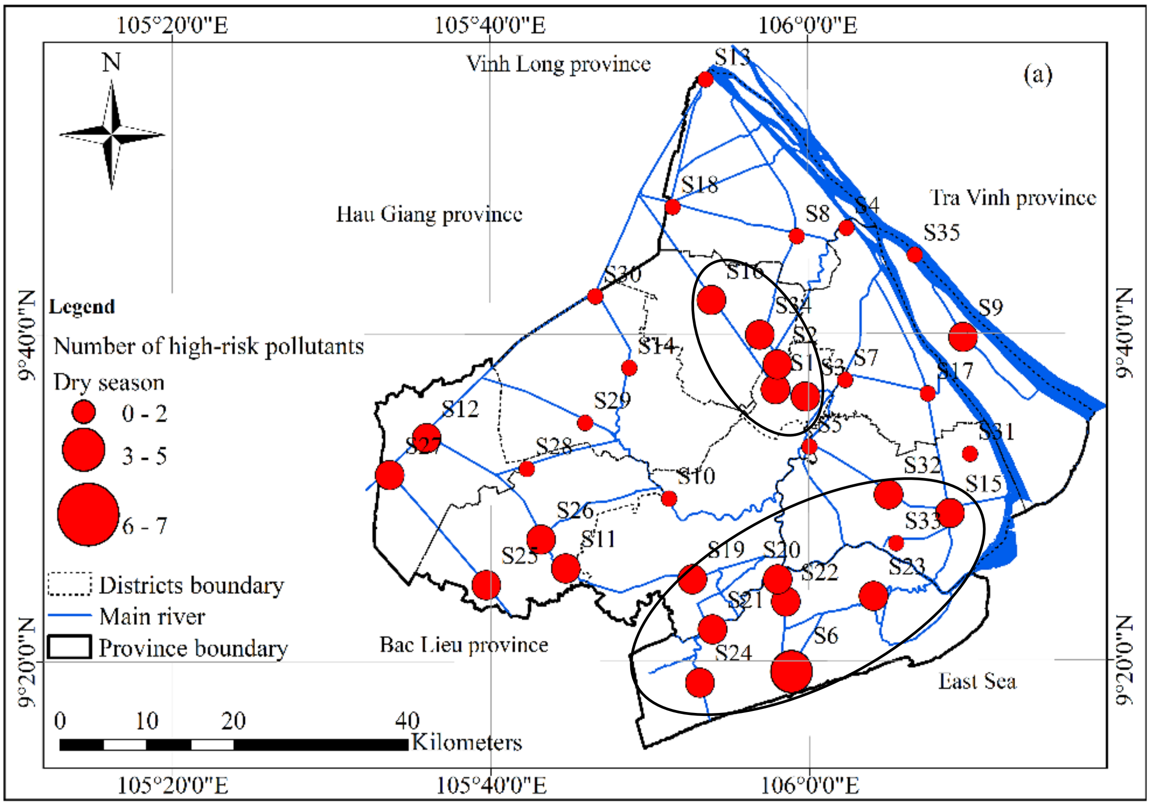
Table 3. Seasonal changes of RQ and risk level ratio of water pollutants

Par.	Dry season							Rainy season						
	RQ			Risk level ratio (%)				RQi			Risk level ratio (%)			
	Mean	Min	Max	N	L	M	H	Mean	Min	Max	N	L	M	H
TSS	4.65	1.19	12.01	0.0	5.7	40.0	54.3	4.65	1.92	8.76	0.0	2.9	34.3	62.9
BOD	1.12	0.65	1.72	8.6	85.7	5.7	0.0	1.18	0.73	1.57	8.6	88.6	2.9	0.0
COD	3.14	1.42	4.72	0.0	8.6	34.3	57.1	3.03	1.10	4.21	0.0	17.1	22.9	60.0
NH_4^+-N	1.48	0.11	6.04	25.7	45.7	17.1	11.4	1.94	0.12	7.38	20.0	31.4	31.4	17.1
NO_2^--N	1.27	0.12	7.87	34.3	51.4	11.4	2.9	1.19	0.16	3.80	42.9	34.3	20.0	2.9
NO_3^--N	0.14	0.05	0.26	100	0.0	0.0	0.0	0.13	0.05	0.27	100	0.0	0.0	0.0
PO_4^{3-}-P	1.28	0.22	15.56	54.3	34.3	8.6	2.9	1.56	0.21	12.89	34.3	54.3	2.9	8.6
Cl^-	2.60	0.12	15.58	37.1	28.6	14.3	20.0	1.14	0.08	6.60	60.0	20.0	5.7	14.3
Fe_{total}	4.64	1.62	10.74	0.0	5.7	22.9	71.4	5.24	1.87	9.71	0.0	2.9	11.4	85.7
Coliform	9.80	0.67	64.13	0.0	11.4	31.4	57.1	7.26	1.27	24.00	0.0	11.4	42.9	45.7

Notes: N – None, L – Low, M – Moderate and H – High

Similarly, the level of impacts and risks in the rainy season tends to be similar to that in the dry season. TSS, COD, Fe_t and coliform were still recorded at high impact and the majority of sampling sites were at high risk. Nevertheless, the level of impact of Cl^- on the environment in the rainy season is low, decreasing compared to the dry season. In contrast, the average RQ values of NH_4^+-N and PO_4^{3-}-P tended to increase the impact level but remained low. In addition, the environmental risk at the locations of these two parameters also increased, shifting from safe to low risk and low to moderate.

The number of pollutants with high environmental pollution risk at locations during the dry and rainy seasons is shown in Figure 4. In the dry season, only the S6 site was recorded with 7 out of 10 pollutants at high risk; this area is closest to the sea and the primary water source for aquaculture. Meanwhile, most of the locations with 3 - 5 out of 10 pollutants have a high risk; the sites are concentrated mainly in the resident and coastal areas. Therefore, if the type of domestic wastewater is not treated thoroughly before being discharged into the environment, it will bring many microorganisms and organic matter into the receiving environment. Organic matter and microorganisms will consume large amounts of oxygen in the water, reducing oxygen levels and disrupting aquatic life [39].



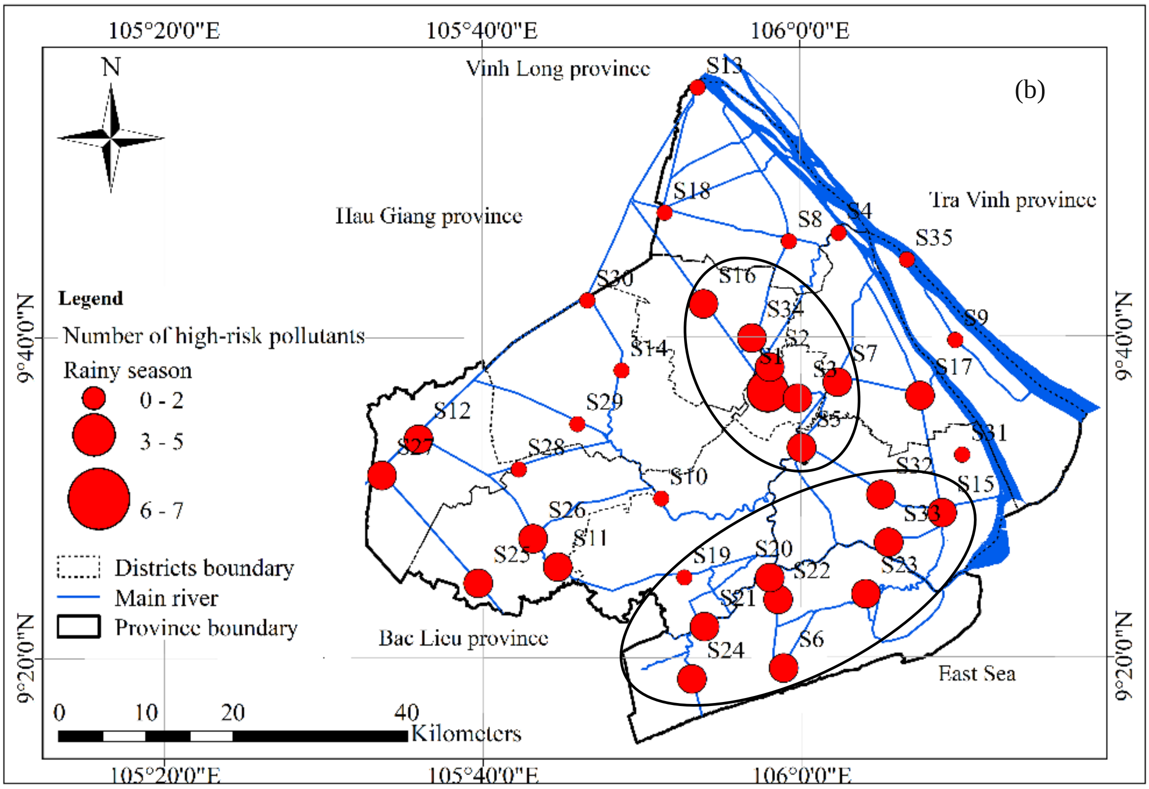


Figure 4. The total number of pollutants with high risks in (a) dry and (b) rainy seasons

In the rainy season, the distribution of locations with a number of high-risk parameters was similar to that of the dry season. However, the number of sites with pollutants at a high environmental risk tended to increase more than in the dry season. Specifically, there are 5 out of 35 positions with many parameters at high-risk level, with about 5-6 parameters.

3.4. Correlation between Overall Surface Water Quality and Risk Quotient

The correlation between the water quality index (WQI) and the impact level of pollutants (RQ_i) is presented in Table 4. During the dry season, the WQI was negatively correlated with RQ_{BOD}, RQ_{COD}, $RQ_{NH_4^+\text{-}N}$ and $RQ_{coliform}$, with the correlation coefficients of (-0.611), (-0.499), (-0.493) and (-0.445), respectively. During the rainy season, the WQI index had a significant negative correlation with RQ_{BOD} (r = -0.703), RQ_{COD} (r = -0.559), $RQ_{NH_4^+\text{-}N}$ (r = -0.531), RQ_{Fet} (r = -0.512) and $RQ_{coliform}$ (r = -0.653) at 1% significance level. Moreover, WQI showed a significant positive correlation with $RQ_{NO_3^-\text{-}N}$ (r = 0.471), indicating that NO_3^--N does not impact the environment. The results of correlation analysis show that the lower the WQI index, the higher the impact level and vice versa.

Table 4. Correlation between overall surface water quality and risk quotient

Index	WQI_Dry season		WQI_Rainy season	
	R	p	R	p
RQ_{TSS}	0.088	0.615	-0.182	0.297
RQ_{BOD}	-0.611**	0.000	-0.703**	0.000
RQ_{COD}	-0.499**	0.002	-0.559**	0.000
$RQ_{NH_4^+\text{-}N}$	-0.493**	0.003	-0.531**	0.001
$RQ_{NO_2^-\text{-}N}$	-0.324	0.058	-0.300	0.080
$RQ_{NO_3^-\text{-}N}$	0.199	0.253	0.471**	0.004
$RQ_{PO_4^{3-}\text{-}P}$	-0.271	0.115	-0.065	0.709
RQ_{Cl^-}	0.142	0.415	-0.058	0.739
RQ_{Fet}	-0.067	0.702	-0.512**	0.002
$RQ_{coliform}$	-0.445**	0.007	-0.653**	0.000

Note: ** Correlation is significant at the 0.01 level (2-tailed)

3.5. Polluting Sources Influencing Surface Water Quality

Principal component analysis (PCA) was performed on a standardized data set to determine the main factors and sources affecting surface water quality in the dry and rainy seasons in 2022. Values of the KMO test in the dry and rainy seasons are 0.521 and 0.609, respectively, with Bartlett's value of 0.00. The KMO test coefficient between 0.5-0.7 and Bartlett less than 0.05 is considered satisfactory [26]. From that, it is found that the PCA analysis data used to explain the change in surface water quality in the study area is entirely appropriate.

In the dry season, PCA identified 6 PCs that explained about 78.63% of the total variance of surface water quality deterioration for the selected parameters (Table 5). The first principal component (PC1) explained 22.99% of the total variance and had a positive load with TSS (0.950) and Fe_t (0.784) at strong, Cl^- (0.728) at moderate and COD (0.442) at weak levels. This PC is explained as pollution related to saline seawater intrusion in the study area. The second principal component (PC2) accounted for 16.89% of the total variance, forming a high negative load with pH (-0.771) and a high positive loading with BOD (0.807). Untreated domestic, aquaculture and industrial production wastewater discharged into the receiving environment in the study area can cause high levels of BOD. BOD and COD had a close relationship, specially formed from industrial and agricultural wastewater discharge containing large amounts of organic matter [36]. The third principal component (PC3) explained 11.69% of the total variance and had a positive loading with NH_4^+-N (0.813) and PO_4^{3-}-P (0.939). This component represents nutrient pollution from agricultural activities and domestic wastewater, especially using detergents that can increase the concentration of PO_4^{3-}-P in water [15, 24, 31].

Table 5. Potential polluting sources of surface water quality

Parameter	Dry season						Rainy season			
	PC1	PC2	PC3	PC4	PC5	PC6	PC1	PC2	PC3	PC4
pH	0.038	-0.771	0.079	0.019	0.276	-0.196	-0.161	-0.069	0.080	0.855
Temp.	-0.153	-0.018	-0.011	0.099	0.818	0.170	-0.062	-0.203	0.545	-0.562
TSS	0.950	0.040	-0.019	-0.101	-0.077	-0.027	-0.203	0.841	0.107	0.202
DO	0.107	-0.333	0.003	-0.439	0.647	-0.133	-0.455	-0.023	-0.522	0.001
BOD	0.162	0.807	0.257	0.008	0.017	-0.008	0.425	0.469	0.470	-0.173
COD	0.442	0.378	0.489	0.425	0.118	-0.078	0.491	0.569	0.290	-0.294
NH_4^+-N	0.011	0.309	0.813	0.291	0.058	0.186	0.831	0.179	0.109	-0.205
NO_2^--N	-0.034	0.110	0.073	-0.042	0.108	0.936	0.006	0.119	0.822	0.222
NO_3^--N	-0.001	-0.025	-0.167	-0.556	0.333	0.029	-0.634	0.084	0.162	0.281
PO_4^{3-}-P	-0.045	-0.074	0.939	-0.054	-0.092	-0.030	0.808	-0.059	0.026	0.194
Cl^-	0.728	-0.446	-0.050	0.049	-0.220	0.272	-0.049	-0.085	0.818	-0.102
Fe_t	0.784	0.419	0.054	-0.024	0.084	-0.217	-0.010	0.896	-0.054	0.065
Coliform	-0.067	-0.072	0.015	0.842	0.132	-0.023	0.177	0.490	-0.200	-0.244
Eigenvalues	2.99	2.20	1.52	1.42	1.09	1.01	3.38	2.12	1.99	1.19
% of Variance	22.99	16.89	11.69	10.90	8.35	7.80	26.00	16.31	15.34	9.18
Cumulative %	22.99	39.88	51.57	62.47	70.82	78.63	26.00	42.31	57.65	66.83

The fourth principal component (PC4) accounted for 10.90% of the total variance, with the contribution of coliform at a high level (0.842) and weakly with COD (0.425). The high concentration of coliform present in water comes from livestock, aquaculture and human activities. At the same time, high coliform density is associated with organic substances at high concentrations [36]. The fifth principal component (PC5) explained 8.35% of the total variance and has a positive load with temperature (0.818), DO (0.647) and NO_3^--N (0.333) at strong, moderate, and weak levels, respectively. The process of nitrification in water requires the right amount of oxygen. However, severe organic, nutritional, and microbial pollution in the study area has depleted oxygen in the water, resulting in relatively low nitrate levels. NO_3^--N in water can come from artificial sources, such as domestic, agricultural, and other waste sources containing nitrogen compounds [23]. The sixth component (PC6) explained 7.80% of the total variance, focusing on explaining the change in surface water quality through the indicator NO_2^--N with the loading coefficient NO_2^--N reaching 0.936. High concentrations of NO_2^--N were mainly in water bodies receiving urban wastewater from domestic and industrial activities in the study area.

In the rainy season, about 66.83% of the total variance of the surface water quality dataset was explained by 4 main components (Table 5). The first principal component (PC1) explained 26% of the total variance and had a strong positive load with NH_4^+-N (0.831) and PO_4^{3-}-P (0.808). In contrast, this significant component formed an inverse correlation with NO_3^--N (-0.634). The loading factor of PC1 suggested that oxygen-consuming pollutants in water may be related to domestic wastewater discharge from urban residential areas, agricultural wastewater and industry [26, 32]. The second principal component (PC2) explained 16.31% of the total variance and was positively strongly correlated with TSS (0.841), COD (0.569) and Fe (0.896). High TSS content in water is often associated with organic and microbial contamination [26].

The third principal component (PC3) explained 15.34% of the total variance, forming a strong correlation with NO_2^--N (0.822) and Cl^- (0.818). During the rainy season, high concentrations of Cl^- are present in the water bodies surrounding the aquaculture areas. Wastewater generated from this area has a high Cl^- content, ranging from 1,645–6,322 mg/L [40]. Similar to the dry season, the concentration of NO_2^--N was only relatively high in the water bodies receiving domestic and industrial wastewater. The fourth principal component (PC4), with 9.18% of the total variance, mainly explains the pH (0.855) with strong loading. The pH of water affects the solubility and availability of nutrients, while the pH affects biological and chemical reactions, the growth of pathogenic microorganisms, as well as the influence of the natural life of aquatic life [26, 40].

4. Conclusion

Surface water quality in the study area has been contaminated with organic matter, nutrients, microorganisms, salinity, and iron. The WQI index in the dry season was assessed from bad to very good and from bad to good in the rainy season. The impact level of TSS, COD, Fe_t, and coliform in both seasons was recorded at a high impact and the risk level of these parameters in the centralized environment is medium and high. The distribution of high-risk pollutants is concentrated in residential and coastal areas. The negative correlation between the WQI index and the RQ index of BOD, COD, NH_4^+-N, Fe_t, and coliform indicated low overall water quality as the impact was high. The water quality indicators that pose ecological risks in the studied water bodies include TSS, BOD, COD, NH_4^+-N, PO_4^{3-}-P, Cl^-, Fe_t, and coliform derived from natural conditions (acid sulfate soil, rainwater runoff), wastewater (domestic, aquaculture, livestock, cultivation, industry), and seawater intrusion. The results show that further strengthening surface water quality management solutions is necessary to minimize environmental risks.

5. Declarations

5.1. Author Contributions

Conceptualization, N.T.G.; methodology, N.T.G; software, H.T.H.N. and L.T.D.M.; validation, N.T.G., H.T.H.N., and L.T.D.M.; formal analysis, H.T.H.N. and L.T.D.M.; investigation, N.T.G.; resources, N.T.G.; writing—original draft preparation, N.T.G., H.T.H.N., and L.T.D.M.; writing—review and editing, N.T.G.; visualization, H.T.H.N.; supervision, N.T.G.; project administration, N.T.G. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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