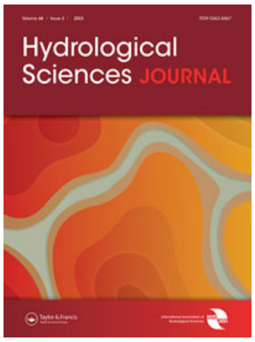

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Spatiotemporal assessment and pollution-source identification and quantification of the surface water system in a coastal region of Vietnam

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Spatiotemporal assessment and pollution-source identification and quantification of the surface water system in a coastal region of Vietnam

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ABSTRACT
Surface water quality in coastal regions may be degraded due to various pollution sources, including seawater intrusion, dependent on season and distance from the coastline. This study aimed to fractionate and quantify pollution sources affecting surface water quality in a coastal region of Vietnam. Between 2016 and 2020, 400 surface water samples were collected from 40 sites during dry and rainy seasons and analysed for 15 parameters. The results showed that four primary pollution sources – seawater intrusion, agricultural production, residential activities, and human activities impacting the hydrological system – may contribute to the degradation of water quality. Seawater intrusion contributed approximately 83.3% to the determination of water quality in dry seasons and 35.3% in rainy seasons. Water quality was more degraded in areas within 20 km of the coastline than in more distant areas. A management strategy should be developed and implemented to improve surface water quality for sustainable development.

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1 Introduction

Surface water systems can be polluted for various reasons deriving from human activities and natural factors (Lin *et al.* 2022). Human activities may include industrial and agricultural production, residential activities, and sewage discharge (Sasakova *et al.* 2018), and natural factors may include climate change (precipitation, humidity, and evapotranspiration) and natural disasters (droughts, floods, and landslide) (Akhtar *et al.* 2021). In particular, the surface water system in coastal regions could be integratively influenced by anthropogenic activities and natural factors (Wilbers *et al.* 2014, Nguyen *et al.* 2021). Wastewater from agricultural, industrial, and residential areas was identified as an important pollution source in degrading surface water quality in various regions (Karbassi *et al.* 2007, Al-Hussaini *et al.* 2018, Alsaffar *et al.* 2018). In addition, human activities such as aquaculture and cargo shipping on rivers may be considered an important pollution source in lowering the quality of the river surface water system (Mutea *et al.* 2021, Muoi *et al.* 2022). The latter could be involved in weather conditions as well as spatial variation, both of which can influence the quality of the surface water system by modifying the impact of pollution sources (Mama *et al.* 2021, Yang *et al.* 2021). Surface water quality in different canals was dependent on pollution sources and seasonal variations (Gomes *et al.* 2019). Furthermore, for a coastal region, seawater intrusion can be considered an important natural factor degrading the quality of the surface water system (Nguyen *et al.* 2021), as it brings salts to freshwater bodies upon landward movement. These pollution sources need to be fractionated and quantified for better management. Moreover, the impacts of these natural and anthropogenic pollution sources could be altered by seasonal variation and spatial variation, which are insufficiently discussed in the literature.

Climate change, characterized by global warming and increasing extreme hydrometeorological events (UNFCCC 2007), has some typical consequences such as changing rainfall regimes and sea-level rise, which shift seawater inland, degrading the surface water quality and many natural ecosystems (Xiao *et al.* 2020, Braun de Torrez *et al.* 2021). Seawater intrusion is a worldwide problem, primarily caused by sea-level rise and climate change (Werner *et al.* 2013, Jeen *et al.* 2021). Many studies have been conducted to investigate the effects of seawater intrusion on the freshwater system and natural risks (Jeen *et al.* 2021, Venâncio *et al.* 2022). Seawater intrusion may cause adverse impacts on socio-economic development in the coastal region, especially in fulfilling the demand for clean water for production and livelihoods (Tuong *et al.* 2003, ADB 2012). Saltwater intrusion can drastically reduce the quality and quantity of surface water in salt-affected areas, depending on the distance from the coast (Paul and Rashid 2017). The water quality in the areas close to the sea may be more influenced by seawater intrusion, while areas farther away may experience lesser impacts. This indicates that the impact of seawater intrusion should be dependent on spatial variation. Furthermore, in tropical regions, which have two distinct seasons (rainy and dry), seawater intrusion may be exacerbated, particularly during the dry season with low rainfall and high temperature.

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Precipitation may alleviate the impact of seawater intrusion by preventing seawater from invading inland areas and by diluting the salt concentration (Xiao *et al.* 2018). This suggests that the combination of these factors could be the real reason for the determination of the surface water quality, which requires further investigation.

The current study was conducted in Kien Giang province, a coastal region of Vietnam. The study area is located at the end of the Hau River in the Mekong Delta region of southern Vietnam. The surface water system in the current study is heavily influenced by various pollution sources, including seawater intrusion and anthropogenic activities, and by seasonal variation. In addition, with a complicated hydrological system, social-economic development, climate conditions, and global sea-level rise, the surface water system in the study area is complexly controlled by various factors, which need to be managed for better development. The current study aimed to fractionate and quantify different pollution sources affecting surface water quality in the study area. We hypothesize that of the many pollution sources, seawater intrusion is the most important one determining the quality of the surface water system; that surface water quality in areas located close to the coast is more degraded than that in other areas; and that water quality is poorer in the dry season than in the rainy season.

2 Materials and methods

2.1 Study area

The current study was conducted in the coastal province of Kien Giang, the southernmost region of Vietnam, situated on the western edge of the country at 9°32′20” to 10°32′26” N and 101°30′07” to 105°32′06” E (Fig. 1). It has an area of around 6348 km^2, a population estimated at about 1 723 695 people in 2019, and a density of 272 people/km^2. The province has 15 administrative units (DS 2020), including 13 districts and provincial cities in the inland area and two island districts, Phu Quoc and Kien Hai, which were not included in the current study. Kien Giang has a diverse landscape that includes plains, mountains, forests, and islands. The mainland, in particular, has relatively flat terrain that slopes downward from northeast to southwest. Kien Giang has a tropical monsoon climate that is warm and humid year round due to its low latitude and proximity to the sea, with an average monthly temperature of 27 to 27.5°C. The province has a total annual rainfall of 1593.4 to 2630.1 mm (DS 2020), divided into dry and rainy seasons (see Supplementary material, Table S1). The province has a dense hydrological network of 2927 rivers and canals with a total length of 2055 km, including the two largest rivers, Cai Lon (60 km) and Cai Be (92 km). The surface water system in the current study consists of canals or rivers, which

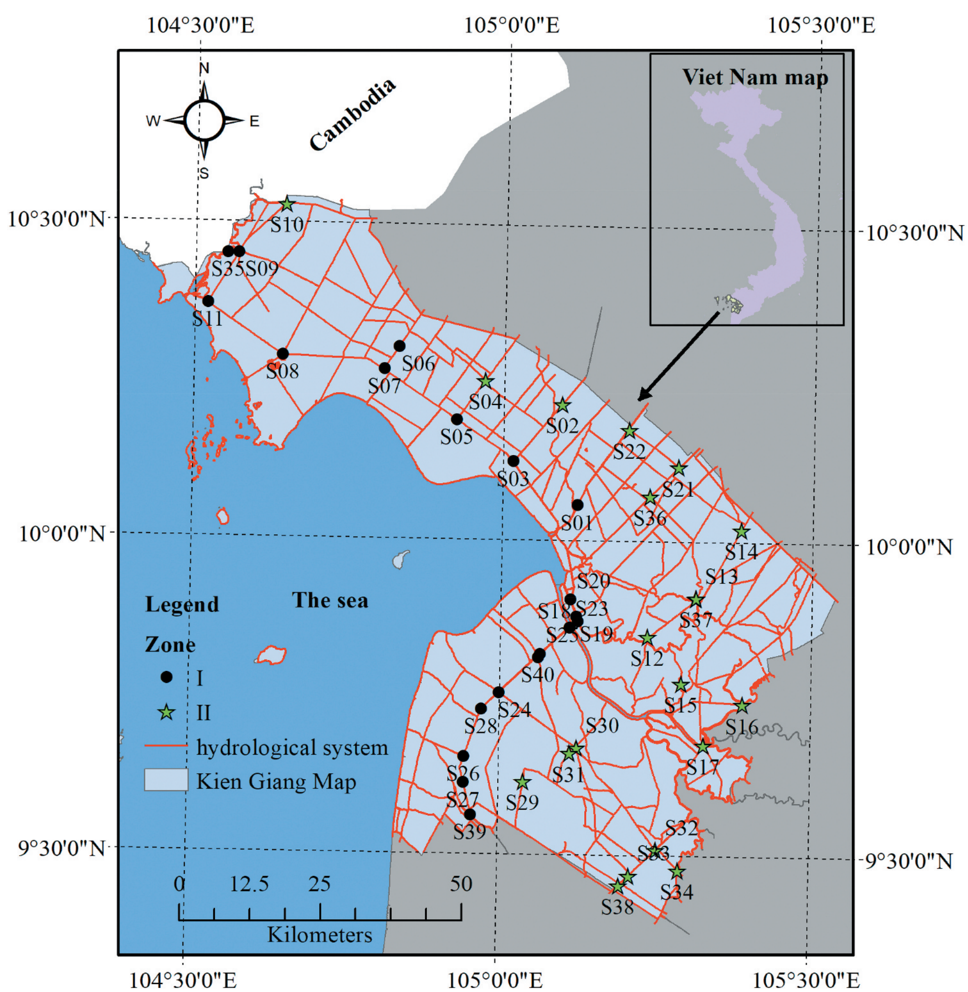

Figure 1. Map of the study area and sampling site in Kien Giang province, Vietnam. S1 to S40 are denoted for sampling sites.

are typically narrow and short, with a few large exceptions. The surface water system plays an important role in draining excess water, directing floodwaters from inland fields to the West Sea, and supplying water for irrigation and transportation.

2.2 Experimental set-up

This study focused on the surface water system, including rivers and canals, in Kien Giang province. The study was designed to collect surface water samples from 40 pre-selected sites distributed over the study area (Fig. 1). Because seasonal variation is considered an important natural factor influencing surface water quality, water samples were taken in two campaigns each year during dry and rainy seasons (see Supplementary material, Table S1). The dry season, lasting from December to May, had total monthly rainfall varying from 0 to around 200 mm/month, and the rainy season, from June to November, had total monthly rainfall ranging from 92 to 497 mm/month in the five-year period from 2016 to 2020 (see Supplementary material, Table S1). Surface-water samplings were implemented in the middle of each season to maximize seasonal effects. Additionally, the distance between sampling sites along the shortest waterway and the coastline was measured from a digital Geographic Information System (GIS) map and used as an experimental factor of spatial variation to explain the variation in surface water quality. Because the effects of seawater intrusion may be dependent on the distance from the coastline, we examined the relationship between surface water quality and the coastline-derived distance and separated the spatial distance into two zones. Zone 1 included 20 sampling sites located within 20 km of the coast, while zone 2 had another 20 sampling sites between 20 and 63 km from the coast (Fig. 1).

2.3 Water sampling and analysis

Based on the experimental set-up, 400 surface water samples (40 sites × 2 sampling campaigns/year × 5 years) were taken for five years (from 2016 to 2020) using a Van Dorn water sampler (Fig. 1). Water samples were taken in the 0–50 cm surface layer. For each surface sample, eight samplers distributed across the cross-section of the river or canal at the pre-selected sites were taken into a plastic container an,d finally, around 5 L of water from this container was further taken into a plastic bottle with a firm cap, which was immediately stored in an icebox at 4°C and transported to a laboratory for measurements. Water remaining in the container was measured directly for temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) using a thermometer, a pH meter (Thermo Scientific™ Orion™ 3-Star Benchtop pH Meter), an EC meter (Oaklon conductivity, TDS, °C Meter, Con 11 series), and a portable DO meter (Oxygen 3210 portable dissolved oxygen Meter), respectively. The water samples in plastic bottles were then transferred to the laboratory for analysis of 11 parameters (Cl^-, salinity, NH_4-N, NO_2-N, NO_3-N, total suspended solids (TSS), PO_4^{3-}, five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total Fe, and total coliform) on the same sampling day (Table 1). The 11 water parameters were determined in the laboratory following the national standard methods (MONRE 2015) and (Nguyen *et al.* 2019). A titration method was used to determine the Cl^- concentration in water samples (Hajrasuliha *et al.* 1991).

2.4 Data analysis

There are many models used to calculate the water quality index and these models have a general common feature of having a fixed set of water parameters (Mahapatra *et al.* 2012, Uddin *et al.* 2021). Similarly, the model by the Vietnam Environment Administration (WQI_VN) also uses a fixed set of 27 water parameters (MNRE 2019), which may not better reflect the water quality in coastal regions, which can be strongly affected by seawater intrusion. In the current study, we additionally measured the water parameters EC, salinity, and Cl^- to better capture the effects of seawater intrusion. Therefore, the principal component analysis/factor analysis (PCA/FA) method was used to compute and assess WQI in the current study.

Before performing PCA/FA, the entire dataset was subjected to the Kaiser-Meyer-Olkin (KMO) and Bartlett's test of sphericity to determine the dataset's suitability for PCA/FA (Banda and Kumarasamy 2020). The current study obtained a satisfactory overall KMO value of 0.71 and a Bartlett's significance level of less than 0.0001. The test results indicated that the entire dataset in the current study was suitable for PCA/FA. The PCA/FA was applied to the entire dataset to

Table 1. Averaged values and standard deviation (SD) of 15 measured water parameters.

Parameters	Unit	Mean	SD	Methods
Temperature	°C	29.45	0.97	Thermal meter
pH	N/A	7.00	0.53	pH meter
Salinity	‰	5.01	5.98	(MONRE 2015)
EC	$\mu S\ cm^{-1}$	6190.09	10 343.29	EC meter
DO	$mg\ L^{-1}$	4.73	0.56	Dissolved oxygen meter
TSS	$mg\ L^{-1}$	48.57	25.95	(MONRE 2015)
BOD_5	$mg\ L^{-1}$	15.08	15.08	
COD	$mg\ L^{-1}$	28.60	8.48	
Cl^-	$mg\ L^{-1}$	2290.33	4274.97	(Hajrasuliha *et al.* 1991)
NH_4^+	$mg\ L^{-1}$	0.26	0.22	(MONRE 2015)
NO_3^-	$mg\ L^{-1}$	0.26	0.21	
NO_2^-	$mg\ L^{-1}$	0.14	0.16	
PO_4^{3-}	$mg\ L^{-1}$	0.28	0.18	
Fe	$mg\ L^{-1}$	0.96	0.80	
Coliform	$MPN\ 100\ mL^{-1}$	79 024.05	253 196.04	

fractionate pollution sources following detailed descriptions by Eqani *et al.* (2011) and Phung *et al.* (2015). PCA/FA results were also used to determine the weightage (w_i) of individual parameters. The usefulness, rationale, and significance of this method were discussed by Mukherjee and Lal (2014). Varimax factors having an eigenvalue greater than 1 were retained for weightage estimation of the water parameters having a high loading value (correlation coefficient between original variables and the latent factor, >0.5) with the corresponding varimax factor.

The water quality index (WQI) was calculated based on the 15 measured parameters and the PCA/FA results (Mukherjee and Lal 2014, Nguyen *et al.* 2021). In brief, WQI was calculated using Equation (1):

$$WQI = \sum_{i=1}^{n} w_i\ s_i \tag{1}$$

where n is the number of water parameters, w_i is the weightage of the ith parameter, and s_i is the score of the ith parameter. w_i was determined using the PCA/FA results (Table 2) via Equations (2) and (3). The 15 water parameters were divided into three groups, which were "more is better," "less is better," and "neutral." The more-is-better parameter includes only DO; the neutral parameters include pH, which should vary from 6 to 8.5 (MONRE 2015), and temperature; and the less-is-better group includes the remaining 12 parameters. For the more-is-better and neutral parameters, s_i was determined following Equation (2).

$$s_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{2}$$

For the less-is-better parameters, s_i was determined following Equation (3):

$$s_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{3}$$

where x_i, x_{min}, and x_{max} were the measured, minimum, and maximum values of parameter i, respectively.

Componential WQIs were computed based on the latent factors extracted from PCA/FA (Table 2) and water parameters having a high loading value with the associated factor, following Equation (4):

$$\text{Componential SQI} = \sum_{j,i=1}^{z} w_i\ s_i \tag{4}$$

where z was the number of soil parameters having high loading value with factor j (j = 1 . . . 6). The relationship between WQI and coastline-derived distance was examined using a scatter plot method and linear and/or non-linear models were determined based on the shape of the scatter plot, r^2 value (coefficient of determination), and a 95% confidence level (P ≤ .05). Analysis of variance (ANOVA) was performed using a two-factor completely randomized design with varying replicates. The statistical model for the ANOVA is: $\gamma_{ije} = \mu + \beta_i + \alpha_j + \alpha\beta_{ij} + \varepsilon_{ije}$, where γ_{ije} is the response of individual combinations of two experimental factors (spatial zone and season); μ is the overall mean of the whole dataset; β_i is the effect of the ith spatial zone; α_j is the effect of the jth season; $\alpha\beta_{ij}$ is the interaction effect between spatial zone and season; and ε_{ije} is the random error with a mean zero and normal distribution (Akhtar and Memon 2009). When ANOVA results showed a significant effect with P ≤ .05, Tukey's honestly significant difference test was used to classify mean values. The multivariable regression analysis was performed to quantify the percentage of six PCA/FA-extracted factors (pollution sources) that contributed to the determination of the total variance of the WQI (Putri *et al.* 2018). Data in tables and figures are shown as average ± standard deviation. Statistical analyses were performed using JMP pro 16 (SAS Institute Inc, NC, USA). All figures were created using Sigmaplot 12 software (Systat Software Inc.).

3 Results

3.1 Latent factors of the entire dataset

The averaged values of the 15 measured water parameters are shown in Table 1, and their correlation coefficients are also presented (see Supplementary material, Table S2). These parameters were subjected to PCA/FA, which showed that the whole dataset of the study areas could be divided into six latent

Table 2. Loading values of 15 water quality parameters from principal component analysis/factor analysis. Bold numbers are those greater than 0.5.

Parameter	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Parameter weightage
EC	**0.92**	−0.07	−0.04	−0.07	0.07	0.01	0.11
Salinity	**0.89**	−0.13	−0.04	−0.03	0.05	−0.03	0.11
Cl^-	**0.88**	0.03	−0.06	−0.09	0.12	−0.08	0.11
pH	**0.54**	0.29	−0.06	0.09	−0.36	0.40	0.11
NO_2^-	0.25	0.02	**−0.74**	0.17	−0.17	0.01	0.04
BOD_5	−0.07	**0.95**	0.07	−0.09	0.05	0.03	0.06
COD	−0.10	**0.94**	−0.01	0.13	−0.06	−0.01	0.06
Log (coliform)	**−0.56**	0.26	−0.01	0.24	0.02	0.25	0.11
DO	0.17	0.09	**0.75**	0.29	−0.10	0.03	0.04
NO_3^-	−0.41	−0.02	0.28	−0.36	**−0.49**	−0.21	0.03
PO_4^{3-}	−0.07	0.02	0.13	**0.85**	0.00	−0.06	0.04
NH_4^+	−0.02	0.01	0.08	−0.07	**0.75**	−0.03	0.03
Fe	**−0.53**	0.01	−0.07	−0.10	0.35	−0.14	0.11
Temperature	0.23	−0.02	0.11	−0.33	0.24	0.04	0.00
TSS	−0.09	−0.01	0.02	−0.09	0.01	**0.92**	0.03
Eigenvalue	3.72	2.03	1.26	1.24	1.08	1.02	
Percentage	24.80	13.52	8.39	8.25	7.22	6.82	
Cumulative percentage	24.80	38.32	46.71	54.96	62.18	69.00	
Factor weightage	0.36	0.20	0.12	0.12	0.10	0.10	

factors, which together accounted for 69.0% of the total variance of the entire dataset (Table 2). The main factors (Factor 1), accounting for 24.80% of the total variance, had a high load value (>0.5) with six parameters, including EC, salinity, Cl^-, pH, log(coliform), and total iron (Fe). The second factor (Factor 2) accounted for 13.52% of the total variance and had a high correlation coefficient with BOD_5 and COD. Similarly, the third factor (Factor 3) had a high loading value with NO_2^- and DO, which were responsible for 8.39% of the total variance of the entire dataset. Factor 4 had a significant loading value with PO_4^{3-}; Factor 5 had a great correlation coefficient with NO_3^- and NH_4^+; and Factor 6 had a high loading value of TSS. The last three factors accounted for 8.25, 7.22, and 6.82%, respectively, of the total variance of the whole dataset.

3.2 Surface water quality

Surface water quality was assessed through the surface water quality index (WQI). The WQI significantly increased from the coastline to the sampling sites in the dry season, following an exponential model, whereas it did not change significantly from the coastline to sampling sites in the rainy season (Fig. 2(a)). During the dry season, when the coastline-derived distance increased from 2.9 to around 20 km, the modelled WQI rapidly increased from 0.68 to around 0.73 and then leveled off. Therefore, the study area was spatially divided into two spatial zones, of which zone 1 included sampling sites within 20 km of the coastline, and zone 2 included sampling sites between 20 km and 63 km from the coastline. Figure 2(b) showed that there was a significant interaction effect between the season and spatial zone on the WQI. In zone 1, the WQI was greatly higher in the rainy season (0.74) than in the dry season (0.7), while in zone 2, the WQI was similar between the two seasons, varying from 0.74 to 0.75.

The whole dataset in the current study could be separated into six factors, and componential WQIs associated with the six factors were computed and are shown in Fig. 3. The componential WQI corresponding to factor 1 in the dry season increased exponentially over the 63-km range of coastline-derived distance, while it varied nonsignificantly over the range in the rainy season (Fig. 3(a)). The exponential WQI associated with factor 3 in both seasons decreased proportionally, following a simple linear regression model when the coastline-derived distance increased from 2.9 to 63 km (Fig. 3(c)). The exponential WQI associated with factor 6 in the dry season declined significantly, while that in the rainy season did not change over the distance (Fig. 3(f)). The exponential WQIs associated with factors 2, 4, and 5 varied nonsignificantly over the coastline-derived distance in both seasons (Fig. 3(b,d,e)).

3.3 Water quality parameters in two zones and two seasons

Six water quality parameters having a high loading value with factor 1 are shown in Fig. 4. The pH was not significantly affected by the interaction of the season and spatial zone, but was influenced by seasonal variation (Fig. 4(a)). The dry season had a greater pH (7.2) than the rainy season (6.8). The salinity, EC, and Cl^- concentration were significantly influenced by the interaction of seasonal variation and spatial zone. In zone 1, the dry season had a higher magnitude of these three water parameters (10.07 g L^{-1}, 16326 μS cm^{-1}, and 6341 mg L^{-1}, respectively) than the rainy season (3.02 g L^{-1}, 2291 μS cm^{-1}, and 792 mg L^{-1}, respectively) (Fig. 4(b,c,e)). Meanwhile, in zone 2, the two seasons exhibited similar salinity (varying from 3.04 to 4.00 g L^{-1}) and EC (varying from 1726 to 4580 μS cm^{-1}). In zone 2, the Cl^- concentration was greatly higher in the dry season (1527 mg L^{-1}) than in the rainy season (559 mg L^{-1}). The Fe concentration was not affected by the interaction of spatial zone and seasonal variation but was influenced by the season (Fig. 4(d)). The rainy season had a higher Fe concentration (1.25 mg L^{-1}) than the dry season (0.68 mg L^{-1}). Coliform density in water was greatly influenced by the interaction of the season and spatial zone (Fig. 4(f)). In zone 1, the coliform density was significantly higher in the rainy season than in the dry season, while in zone 2, the density was similar in the two seasons.

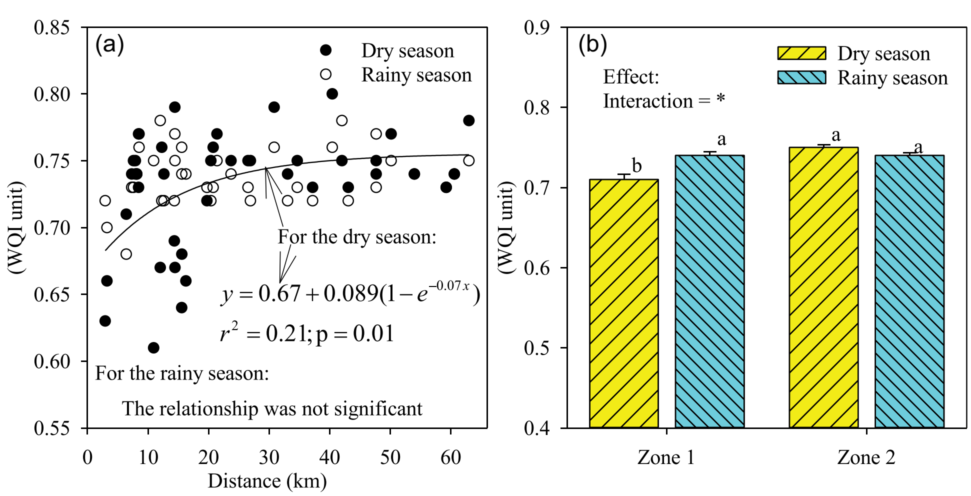

Figure 2. The relationship between (a) the water quality index (WQI) and the coastline-derived distance in the two seasons and (b) WQI in two zones and two seasons. * indicates the interaction effect was significant. Error bars indicate the standard deviation of the mean. Within panel (b), bars with the same letter are not significantly different from each other.

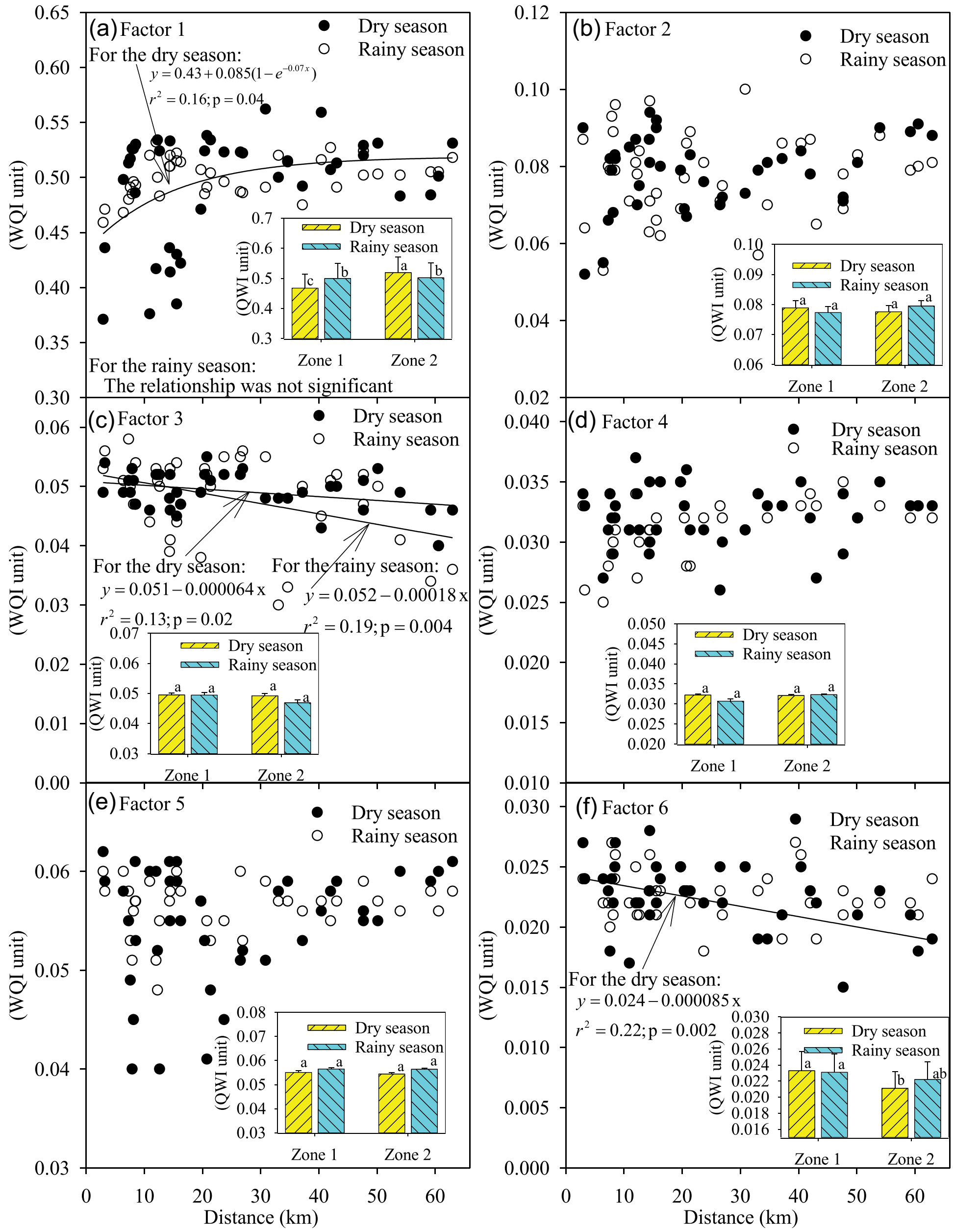

Figure 3. Variation of componential water quality indexes (WQIs) associated with the six factors along the 63-km distance from the coastline in two seasons. The inset bar charts show averaged componential WQIs in two zones and two seasons with ANOVA results. Within the insets, bars with the same letter are not significantly different from each other.

The interaction effect of the spatial zone and seasonal variation, as well as their main effects, was not significant on the magnitude of BOD_5 and COD (Fig. 5(a,b)). The BOD_5 value varied from 14.4 to 15.5 mg L^{-1}, and COD ranged from 27.6 to 29.5 mg L^{-1}. The DO concentration was not affected by the interaction of the spatial zone and season but was influenced by the zone (Fig. 5(c)). Zone 1 exhibited a higher DO concentration (4.78 mg L^{-1}) than zone 2 (4.53 mg L^{-1}). The NO_2^- concentration was greatly influenced by the interaction between the spatial zone and season (Fig. 5(d)). In zone 1, the NO_2^- concentration was similar between the two seasons, while in zone 2, the rainy season exhibited a greater NO_2^- concentration (0.18 mg L^{-1}) than the dry season (0.11 mg L^{-1}).

Of the four water quality parameters shown in Fig. 6, the PO_4^{3-} concentration was significantly influenced by the interaction of the spatial zone and season, while the other three parameters were not. In zone 1, the rainy season showed a greater PO_4^{3-} concentration (0.34 g L^{-1}) than the dry season (0.26 g L^{-1}), while in zone 2, the two seasons exhibited a similar PO_4^{3-} concentration (Fig. 6(d)). The TSS concentration was higher in zone 2 (52.3 mg L^{-1}) than in zone 1 (44.7 mg L^{-1}) (Fig. 6(a)), while NH_4^+ concentration was greater in zone 1 (0.28 mg L^{-1}) than in zone 2 (0.23 mg L^{-1}) (Fig. 6(b)). The dry season had a higher NO_3^- concentration (0.30 mg L^{-1}) than the rainy season (0.22 mg L^{-1}) (Fig. 6(c)).

The multivariable regression analysis showed the WQI was strongly related to the six factors extracted from PCA/FA (Table 3). In the dry season, factor 1 accounted for 83.33% of the total variance of the WQI, and factors 2, 3, 4, 5, and 6 were responsible for 12.96, 1.21, 0.21, 1.30, and 0.98%, respectively.

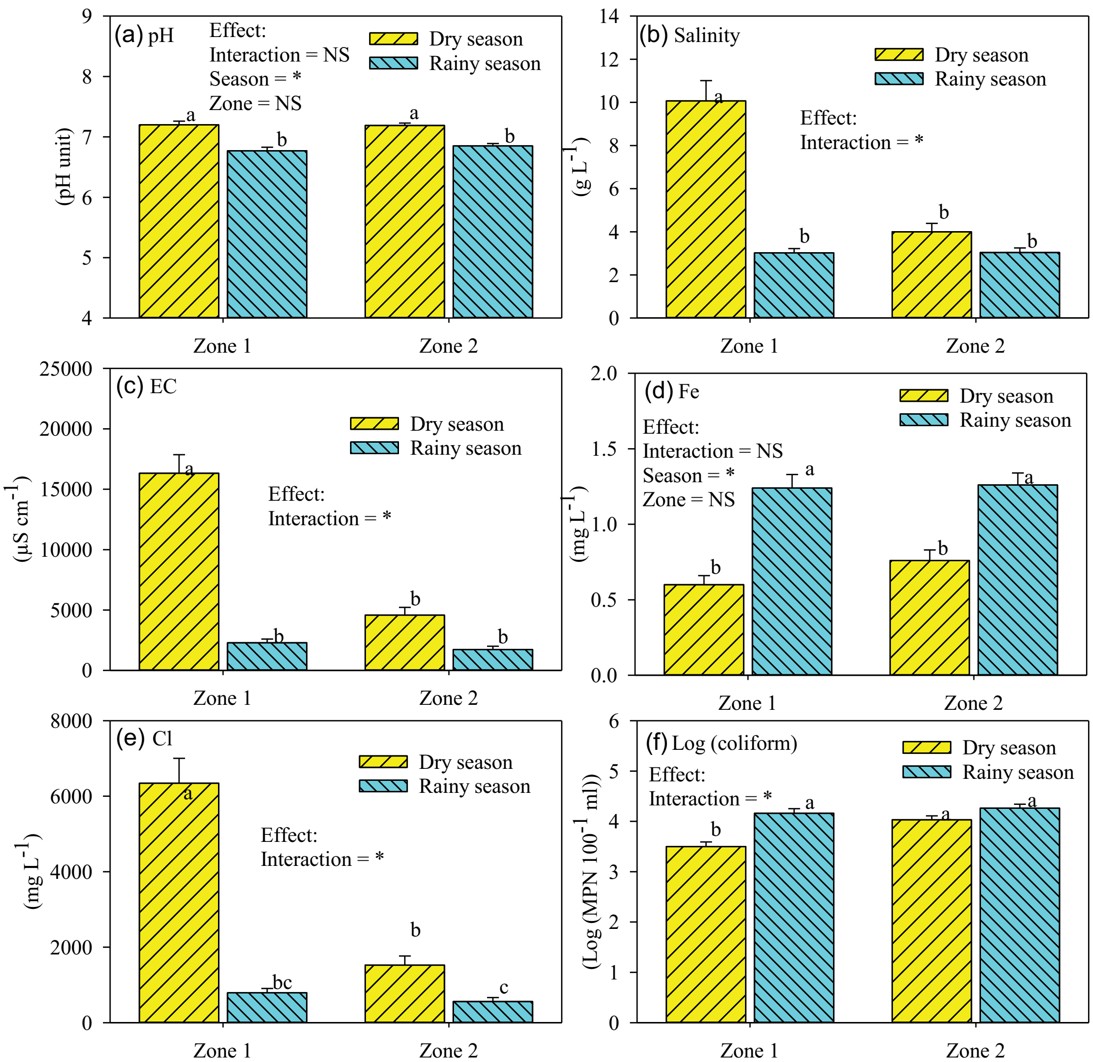

Figure 4. The magnitude of six water parameters having great loading value with factor 1. * and NS indicate the associated effect is significant and nonsignificant, respectively. Within each panel, bars with the same letter were not significantly different from each other. Error bars indicate the standard deviation of the mean.

In the rainy season, factors 1, 2, 3, 4, 5, and 6 accounted for 35.32, 9.83, 2.53, 0.47, 0.56, and 0.38% of the total variance of the WQI, respectively. Together, the six factors explained 99.99% and 49.07% of the total variance of the WQI in the dry and rainy seasons, respectively.

4 Discussion

The six factors were extracted from PCA/FA (Table 2), which was applied over the entire dataset, suggesting that there could be six pollution sources that contributed to the deterioration of surface water in the study area. Factor 1, having high loading values with six water parameters (Table 2), including EC, salinity, Cl^-, pH, Log(coliform), and Fe concentration, which were significantly correlated with each other (see Supplementary material, Table S2), may be representative of the pollution source of seawater intrusion. As a consequence of seawater intrusion, the componential WQI derived from factor 1 rapidly increased from the coastline to the inland area within a 20-km distance (Fig. 3(a)), suggesting that seawater intrusion strongly degraded the surface water of the study area. The decline in salinity, EC, and Cl^- concentration from zone 1 to zone 2 (Fig. 4) may confirm the deteriorating effect of seawater intrusion. Seawater intrusion is the main cause of increasing EC and Cl^- concentration in surface water and groundwater in the river basins (Ahmed and Askri 2016, Nguyen *et al.* 2021). In addition, saltwater intrusion elevated salinity and pH, while decreasing coliform density, reducing the water quality and the use of salt-affected water resources (Okello *et al.* 2015, Mateo-Sagasta *et al.* 2018, World Bank 2020). At present, saltwater intrusion is becoming increasingly serious in the study area due to global climate change, which has a great influence on human activities, food security, and the safety of natural resources (Paul and Rashid 2017). Furthermore, the effect of seawater intrusion may also depend on seasonal variations. High rainfall over the study area during the rainy season may increase water flow and river hydraulics, pushing seawater away from invading the inland area. Similarly, river water was found to move upstream from the estuary during the dry season, while it moved downstream during the rainy season due to freshwater discharge in Casamance and Soungrougrou rivers, West Africa (Descroix *et al.* 2020). This could explain the weak relationship between the componential WQI derived from factor 1 and the coastline-derived distance in the rainy

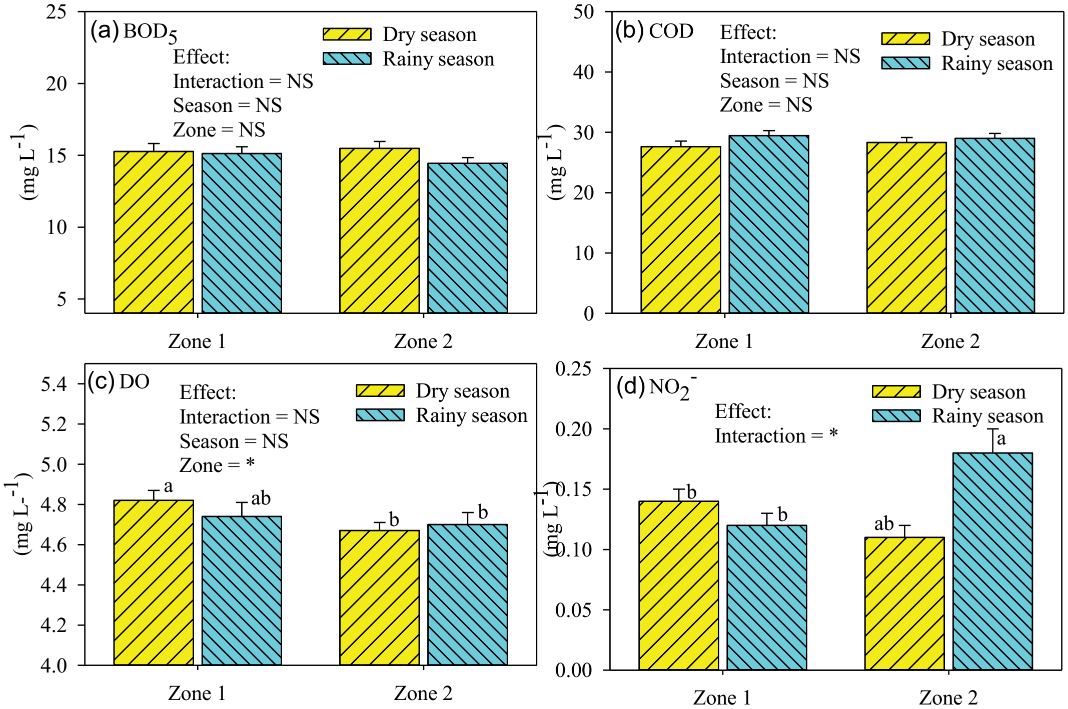

Figure 5. The magnitude of four water parameters having a significant correlation coefficient with factors 2 and 3. * and NS indicate the associated effect is significant and nonsignificant, respectively. Within each panel, bars with the same letter were not significantly different from each other. Error bars indicate the standard deviation of the mean.

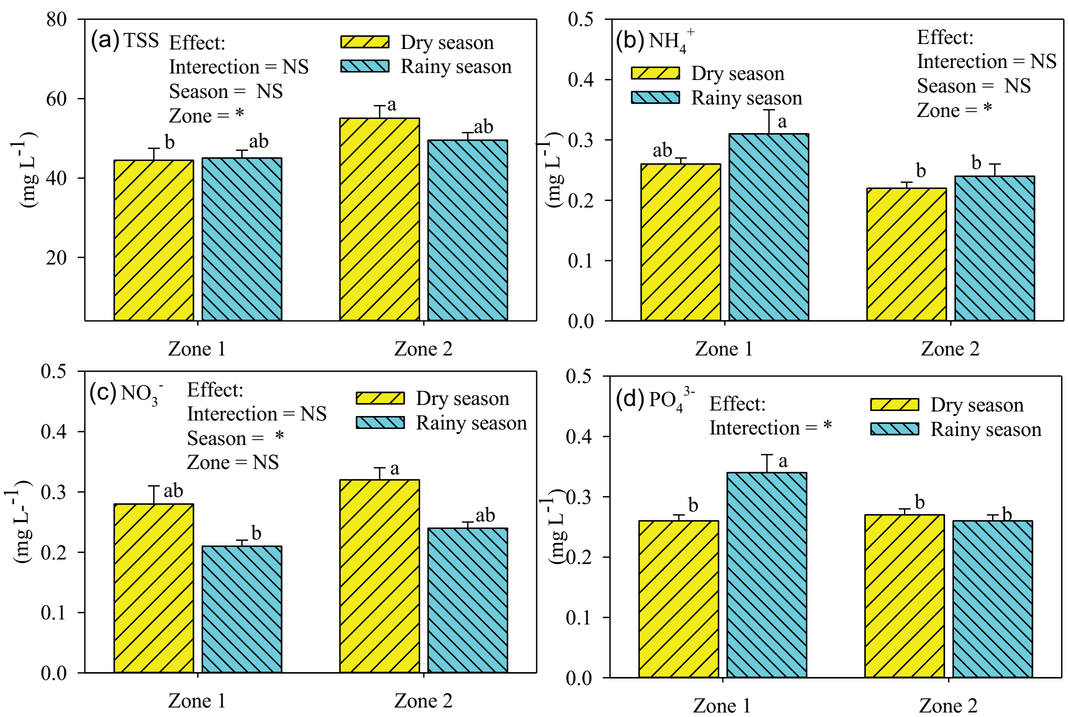

Figure 6. The magnitude of four water parameters having a strong relationship with factors 4, 5, and 6. * and NS indicate the associated effect is significant and nonsignificant, respectively. Within each panel, bars with the same letter were not significantly different from each other. Error bars indicate the standard deviation of the mean.

season (Fig. 3(a)). In contrast, less rain during the dry season may add limited freshwater to the study area, facilitating seawater intrusion, lowering water quality in zone 1 and during the dry season (Fig. 2). Different from the above parameters, Fe may be derived from inland sources, which could be eroded and transported to surface water bodies, raising its concentration in the rainy season, compared to the dry season (Fig. 4 (d)). Washing alum from acid sulfate soil for agricultural production (Donre 2020, Nguyen *et al.* 2020) and runoff over agricultural land (Ha *et al.* 2011, Maprasit *et al.* 2018, Ofosu

Table 3. Percentage of individual factors extracted from principal component analysis/factor analysis in explaining the total variance of the WQI of the study area. * the effect of the considered factor is significant.

	Dry season			Rainy season		
Factors	Sum of squares	Prob > F	Contribution (%)	Sum of squares	Prob > F	Contribution (%)
Factor 1	0.588	<.0001*	83.33	0.247	<.0001*	35.32
Factor 2	0.091	<.0001*	12.96	0.069	<.0001*	9.83
Factor 3	0.009	<.0001*	1.21	0.018	<.0001*	2.53
Factor 4	0.001	<.0001*	0.21	0.003	<.0001*	0.47
Factor 5	0.009	<.0001*	1.30	0.004	<.0001*	0.56
Factor 6	0.007	<.0001*	0.98	0.003	<.0001*	0.38
Error	0.0001		0.01	0.36		50.93
Total variance	0.71		100.00	0.70		100.00

et al. 2021) could be the causes of increased Fe concentration in surface water bodies in the current study.

The second pollution source associated with factor 2 and responsible for BOD_5 and COD, which were significantly correlated with one another, could be derived from residential areas. Domestic wastewater may contain a high concentration of C-based substances, which may originate from bathrooms, kitchens, and toilets. The discharge of domestic wastewater may contaminate surface water bodies with great levels of BOD_5 and COD. Organic-C contamination of the surface water system was attributed to municipal wastewater discharged from residential areas (Vega *et al.* 1998, Simeonov *et al.* 2003). It was also noticed that the componential WQI associated with factor 2 and the concentration of BOD_5 and COD were not greatly influenced by the seasonal variation and spatial zone or their interaction (Figs. 3(b), 5(a,b)). Although the true reason for this was unknown, one possibility might be related to the relatively even distribution of the residential areas over the whole study area. The study area is a remote and coastal province with a low population density, leading to unclear effects of residential areas on surface water quality with regards to BOD_5 and COD contamination.

The third pollution source could be linked to the emission of inorganic nutrients, such as NO_2^-, PO_4^{3-}, NO_3^-, NH_4^+, and DO into surface water bodies. Crop production and aquaculture could be the primary sources of these water quality parameters. The use of fertilizers in paddy fields may release a large amount of inorganic compounds into the soil and environment (Li *et al.* 2017). Loss of nitrogen and phosphorus from paddy fields (Liu *et al.* 2018, Cui *et al.* 2020) may happen through surface runoff, leading to the enrichment of these inorganic nutrients in surrounding surface water bodies. Aquaculture-derived wastewater may contain a considerable amount of nutrients and suspended solids from excess feed and digestive remnants (Dauda *et al.* 2019), which could be discharged into surrounding environments, polluting the water system. Excess fertilizers (nitrogen, phosphorus, organic fertilizers) can be washed into rivers or channels by overflowing water from residential areas, gardens, and fields (Bertol *et al.* 2010, Li *et al.* 2017), increasing the concentrations of NH_4^+, NO_2^-, NO_3^-, and phosphorus (P) in the surface water system. High NH_4^+, NO_2^-, and NO_3^- concentrations in water may lower the DO concentration due to the increased oxygen demand (Fernandes *et al.* 2018, Xia *et al.* 2018, Hong *et al.* 2019). This may mean that there are numerous factors contributing to the enrichment of these inorganic nutrients in surface water bodies, and crop production and aquacuture could be the primary pollution sources in the current study.

The last important pollution source contributing to the elevation of TSS concentration, which had a high loading value with factor 6 (Table 2), could be related to human activities on the rivers and canals, as well as the transportation of suspended solids from the upper parts of the Mekong River (Donre 2020). Rainwater may detach and carry a great amount of suspended solids and sediment into surrounding surface water (Huang *et al.* 2010, Gong *et al.* 2016), polluting the surface water system. The activities of cargo ships or boats on rivers and canals may disturb sediment from the bottom (Nguyen *et al.* 2021), contributing to the pollution of the surface water with a high TSS concentration.

The four major pollution sources discussed above should have distinct characteristics, which may determine the WQI variation across the spatial zones and seasons (Fig. 2). In zone 1, which included sampling sites located within 20 km of the coastline, the WQI was significantly lower in the dry season than in the rainy season, which could be attributed to salt intrusion from the connecting sea. The findings confirmed our hypothesis of poorer water quality in the dry season than in the rainy season, which could happen in the coastal areas. The intrusion of seawater into inland areas could be determined by rainfall and upstream discharge. Low rainfall and upstream flow during the dry season in the study area may accelerate the saltwater intrusion into the coastal area. Heavy precipitation during the rainy season may keep seawater from invading inland areas, lowering the impact of seawater intrusion. In contrast, in zone 2, which includes sampling sites located beyond the 20-km distance from the coastline, the WQI was similar in the two seasons. The findings could be explained by the similar effects of different pollution sources (saltwater intrusion, agricultural activities, residential activities, and human activities on rivers and canals) on surface water bodies in zone 2.

The change in componential WQIs along the coastline-derived distance and seasonal variations may reflect the important role of saltwater intrusion on surface-water quality (Fig. 3). Of the six factors extracted from PCA/FA, factor 1 corresponding to the pollution source of seawater intrusion showed that its associated componential WQI (Fig. 3(a)) increased exponentially from the coastline to farther areas, which could happen only in the dry season. The other factors showed nonsignificantly changing trends in their associated componential WQIs in both seasons (Fig. 3(b,d,e)), or decreasing trends over the coastline-derived distance (Fig. 3(c, f)). The lower componential WQI in sampling sites located close to the coastal areas (Zone 1) than in sites farther away from the coast, especially in the dry season (Fig. 3(a), may support another research hypothesis that surface water quality in areas located close to the coast is more degraded than that in other areas. The current study also found that seawater intrusion may affect the surface water quality of the areas located within 20 km of the coastline during the dry season. Seawater intrusion into rivers is a natural process, and when it occurs it leads to pollution of surface water systems connecting to the sea. The effects of seawater intrusion could be dependent on the rainfall regime. With high rainfall during the rainy season, the effects of saltwater intrusion were not clearly observed in the whole study area.

Other studies examined the variation of WQI over rivers and found that the surface water quality was degraded from the upper to the lower reaches of the examined rivers (Nguyen *et al.* 2011, Fathi *et al.* 2018, Briciu *et al.* 2020). The primary causes of the decreasing trend in surface water quality could be linked to pollution sources as well as the transport of pollutants from upstream to downstream. Different from these studies, the current study found that the componential WQIs associated with factor 3 in both seasons and factor 6 in the dry season declined from the area close to the coastline to the area far from the line (Fig. 3(c,d)). The current study was based on a hydrological system including small rivers and canals that connected anthropogenic pollution sources to the sea. Water bodies receiving the discharged pollutants directly from their sources could be more polluted, leading to poor water quality, while water bodies near the sea may be diluted with seawater. These could explain the contrasting trends in componential WQIs associated with factors 1, 3, and 6 (Fig. 3). The findings may suggest the water bodies located near the sea may be strongly affected by the seawater intrusion but less influenced by anthropogenic activities and vice versa.

Of the four potential pollution sources identified and discussed above, the source of seawater intrusion was estimated to contribute around 83.33 and 35.32% in the dry season and rainy season, respectively (Table 3), to the determination of surface water quality in the current study. The finding indicates that seawater intrusion was the most important pollution source influencing surface water quality in the study area, especially in areas located within 20 km of the coastline during the dry season. Seawater intrusion was reported to have adverse impacts on groundwater and surface water (Preston and Clayton 2003, Hasan *et al.* 2021, Ashrafuzzaman *et al.* 2022), which need to be controlled for better surface water quality. The current study used water quality data observed in five recent years to fractionate surface water quality into different components, which were primarily determined by four potential pollution sources. Although the current study clearly demonstrates a considerable contribution of seawater intrusion as an important pollution source to the deterioration of the surface water quality, in addition to other pollution sources such as agricultural production and residential activities, more studies on identifying and controlling the pollution sources, particularly during the dry season, are required for sustainable development.

The findings from the current study indicate the coastline-adjacent area was strongly affected by seawater intrusion, with some important water pollutants such as Cl^- and salinity. These pollutants were more severe in the dry season than in the rainy season. Because seawater intrusion is a natural process happening strongly during the dry season, treatment of salt-affected surface water could be possible at a high cost. Identifying seawater intrusion and monitoring the invasion of saltwater could help mitigate its adverse effects. Building upstream dams for water storage, which are used to push saltwater away from the surface water system during the dry season, could be one strategy for dealing with seawater intrusion, particularly in the current era of rapid climate change. Organic compounds (BOD_5 and COD) and inorganic elements such as NO_2^-, PO_4^{3-}, NO_3^-, NH_4^+, and DO were also present in the surface water system in the study area. The pollution sources responsible for these pollutants could be distributed relatively evenly over the study area in the two seasons (Fig. 3). To improve the quality of the surface water system, these pollution sources (residential areas, agricultural activities, and human activities in the hydrological system) should be managed. Wastewater from these sources, except for that of human action on the hydrological system, should be treated before discharge into the environment. In brief, management strategies for mitigating the adverse effects of the pollutants in coastal areas, specifically tailored for seasonal variation, spatial variation, and pollution sources, should be developed for sustainable development.

5 Conclusion

The current study found that in the areas near the coast (within 20 km of the coastline), some water parameters, such as salinity, EC, and Cl^- concentration, were significantly greater in the dry season than in the rainy season, while in more distant areas, similar differences were not found. This suggests that the surface water quality of the study area was more degraded in the areas located around 20 km from the coastline than in the more distant areas, especially during the dry season. The PCA/FA revealed that there may be four primary pollution sources (seawater intrusion, agricultural production, residential activities, and human activities that affect the hydrological system) contributing to the degradation of surface water quality. Seawater intrusion was the most important pollution source, which contributed around 83.3 and 35.3% in the dry and rainy seasons, respectively, to the determination of surface water quality. The effect of seawater intrusion on surface water quality was clearly found during the dry season, suggesting that heavy precipitation during the rainy season may dilute the seawater and/or push it away from the inland water system. Controlling seawater intrusion during the dry season while reducing pollutants discharged from other pollution sources should be implemented to improve the quality of the surface water system in the study area for long-term development.

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Data availability statement

The datasets generated and/or analysed in the current study are available from the corresponding author on reasonable request.

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