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The interactive effects of the seawater intrusion-affected zones and types of waterways on the surface water quality from the coastal Tien Giang Province, Vietnam

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Abstract Although inland surface water bodies have been studied intensively, few studies have looked at the interactive effects of seawater intrusion and waterway types on the water quality. The current study aimed to (1) assess the inland water quality as affected by waterway types and seawater intrusion-affected zones, (2) examine the longitudinal dynamics of the water quality, and (3) quantify the contributive percentage of pollution sources in the coastal Tien Giang Province, Vietnam. A total of 680 surface-water samples were taken from 34 sites distributed over the Tien River and its tributary canals from 2015 to 2019. The water samples were analyzed for 16 physical, chemical, and biological parameters, which were used for water quality index (WQI) estimation and subjected to two-way ANOVA and principal component analysis/factor analysis (PCA/FA). The WQI in both waterway types tended to get better from the downstream to the upstream zone with an improving rate of WQI faster in the River (from 79 to 88) than in the canals (from 82 to 85). The PCA/FA showed that water from the two waterway types could be polluted by six main pollution sources, one of which was derived from the seawater intrusion, one from aquaculture, and the others from agricultural, residential, and industrial activities. In brief, the inland surface water quality of a coastal area was interactively influenced by spatial distance and waterway types, transferring various pollutants in and out of the inland area.

Keywords Agricultural activities · Aquaculture activities · River · Seawater intrusion · Residential activities

Introduction

The inland surface water bodies are receiving increasing interest with many publications all over the world (Behmel et al., 2016; Giri et al., 2020; Tirkey et al., 2013). They are even more important today because of a great relative decline of their resources due to the fast growth of population, industrialization, intensified agriculture, and climate change worldwide (Mateo-Sagasta et al., 2018; Okello et al., 2015; World Bank, 2020). Inland surface water can be used for many purposes, such as water supply for humans, irrigation, and others for industrial production, recreational, and environmental activities. Two aspects of the

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inland water bodies, including quantity and quality, should be considered for protection and conservation. While the former may take a relatively certain long period to change, the latter is much more vulnerable to degradation due to natural processes and anthropogenic impacts (Khatri & Tyagi, 2014; Mateo-Sagasta et al., 2018). Consequently, many studies have been conducted to examine/assess the spatial and temporal changes in the quality of the inland water bodies as well as to apportion associated pollution sources (Behmel et al., 2016; Giri et al., 2020; Tirkey et al., 2013). Although it is essential to mathematically quantify the percentage of pollution sources contributing to degrading the water bodies, limited studies were carried out for this purpose (Putri et al., 2018).

The lower reaches of a river and its tributary canals (two waterway types) are important inland water bodies linking the other water bodies from the inland to the sea. Consequently, water from the inland waterways is potentially polluted by various pollution sources, mainly derived from natural processes and anthropogenic activities (Khatri & Tyagi, 2014) and the seawater intrusion (Paul & Rashid, 2017). The inland waterways could be even seriously polluted today due to the discharge of various wastes as a consequence of the rapid growth of population, industrialization, and urbanization (Al-Hussaini et al., 2018; Alsaffar, 2018; Karbassi et al., 2007). A big difference between the two waterway types (river and its tributary canals) can be involved in the greater water flow on the river while more effects of local pollution sources on the tributary canals, altering the water quality of the two waterway types. On the other hand, with climate change reported (IPCC, 2019), seawater intrusion may contribute to degrading the surface water quality of these water bodies (Paul & Rashid, 2017) increasingly, depending on the distance from the coastline. This indicates that the downstream zone could be affected by the seawater intrusion more seriously than the upstream zone. Eventually, the water quality of the inland waterways connecting to the sea could be interactively influenced by waterway types and the seawater intrusion-affected zones. Nevertheless, limited studies were conducted to address the knowledge gap.

The coastal Tien Giang province is located in the delta of the Mekong River and has one side facing the East Sea of Vietnam. There are many anthropogenic activities (agriculture, urbanization, industry, and aquaculture) discharging untreated wastes directly to the environment, degrading the surface water quality of the province (Pham et al., 2015). In general, the inland surface water in the province is stored in two main types of waterways, which are the Tien River and its tributary canals. These two waterway types inter-connect with each other and with the sea in the east. Consequently, the inland surface water of the area could be additionally influenced by the seawater intrusion. Nevertheless, this pollution source and its interaction with the waterway types in the Tien Giang province are not addressed and discussed (Nguyen et al., 2018; Pham et al., 2015). Besides, the waterways in the area are located in the lower reaches of the Mekong River, which was reported to be degraded (Chea et al., 2016). This degradation could be caused by local pollution sources as well as seawater intrusion, which need more studies to clarify and also quantify their contribution.

Therefore, the current study was conducted to (1) assess the inland water quality as affected by waterway types and seawater intrusion-affected zones, (2) examine the longitudinal dynamics of the water quality, and (3) quantify the contributive percentage of pollution sources in the coastal Tien Giang Province, Vietnam. It was hypothesized that the surface water quality in the studied area was interactively affected by the waterway type and spatial zone; the water quality would get better from the downstream zone to the upstream zone, and some important pollution sources such as seawater intrusion, agricultural, residential activities, and aquaculture could mainly contribute to degrading the water quality of the studied area.

Materials and methods

The study area

The Tien Giang province is a provincial administrative unit, located at 105° 49′–106° 47′E and 10° 34′–10° 11′N in southwestern Vietnam (Fig. 1). The province has the eastern side connecting to the East Sea of Vietnam with a coastline of around 32 km long. With a total area of 2510 km^2, this coastal province is subdivided into 11 district-level divisions, including 8 districts, 2 district-level towns, and a provincial city. The population density of the province

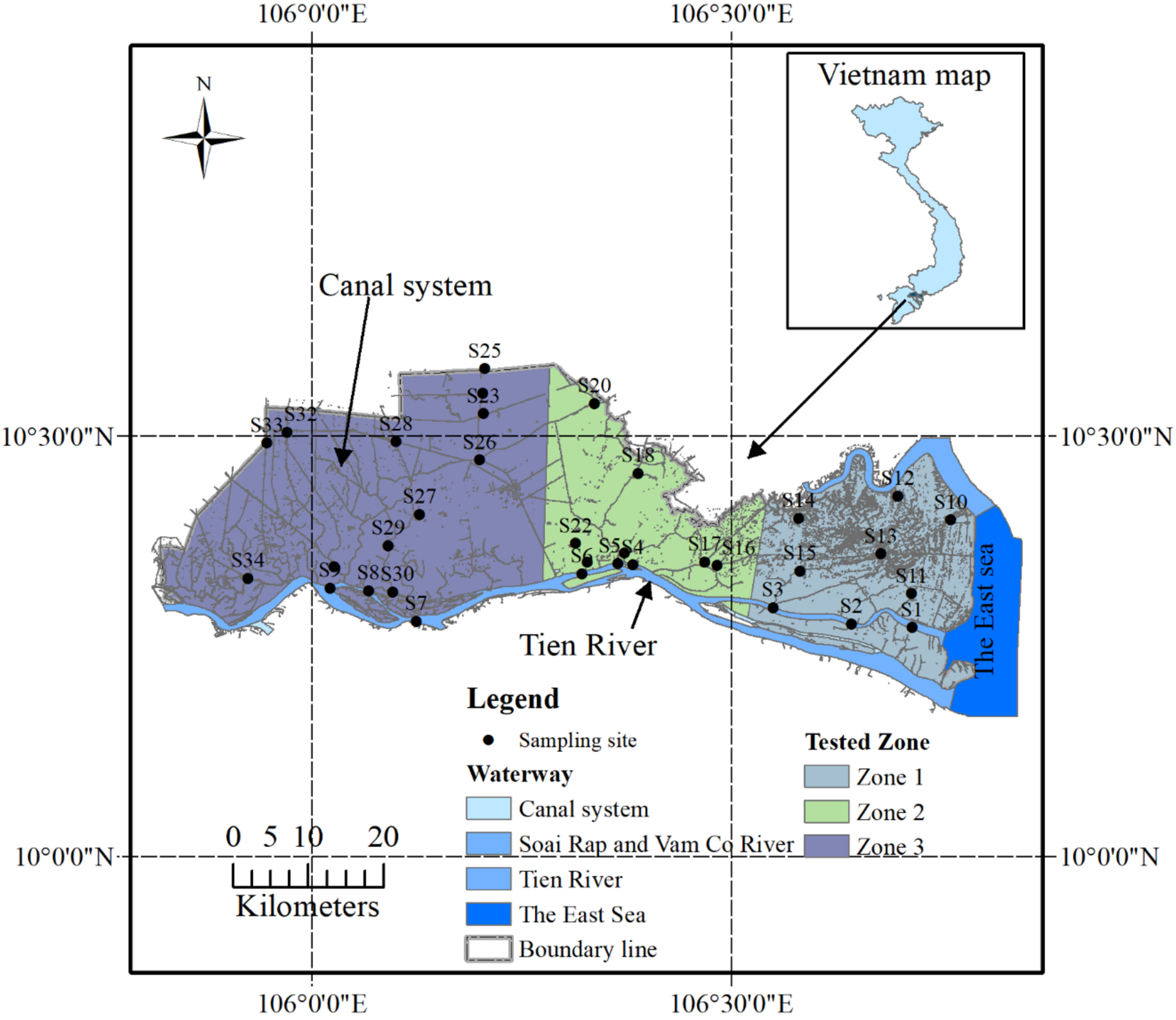

Fig. 1 Sampling sites, tested zones, waterways, and map of the provincial Tien Giang, Vietnam

varies from 180 to 2700 inhabitants per square kilometer, more concentrating in the provincial middle zone (DHATG, 2019). It also has an intertwined hydrological system of 832 km long, formed from two main waterway types, which are the Tien River and its tributary canals. The Tien Giang province is located in a tropical monsoon climate zone, with an average temperature (27–27.9 °C) and an annual rainfall of 1210–1424 mm, separated into dry and rainy seasons.

There are at least four anthropogenic activities that may contribute to polluting surface water bodies in the study area, in addition to the seawater intrusion, including residential activities, industrial production, agricultural activities, and activities of boats and ships on the waterway system. With a high population density in the middle zone of the province (Fig. 1), surface water in the zone may be polluted with domestic sewage characterized by a high concentration of BOD_5 and coliform (CERMoTP, 2017). The study area had many industrial zones and/or industrial clusters (Pham et al., 2015), which are still in development, degrading the surface water of the study area. The effluent discharged from the industrial zones was characterized by a high concentration of COD, BOD_5, total N, and some heavy metals (CERMoTP, 2017).

Agricultural activities that happened in the study area mainly included food crop cultivation, fruit production, and aquaculture. Rice cultivation, one main food crop in the area (Berg et al., 2012), and fruit production may pollute surface water by excess fertilizer application (Nguyen, 2017). The study province also had a large area of 6019 ha for aquaculture production, producing around 20 243 tonnes of fishery products each month (Department of Statistics of Tien Giang, 2019). Three cultural methods including cage, fence, and pond culture, although the last one is currently predominant (De Silva & Nguyen, 2011), were mainly applied in the Tien River and the surroundings for aquaculture production. These indicated that aquaculture may greatly contribute to polluting the surface water system in the study area.

Experimental factors and setup

The current study was set up as a completely randomized design with two factors and varying replicates. The two experimental factors are the seawater intrusion-affected zones and waterway types.

The seawater intrusion-affected zones (spatial zone): The studied area was spatially subdivided into three zones based on the distance from the coastline and the spatial distribution of population density over the whole province (Fig. 1). The downstream zone is about 30 km long started from the coastline, characterized by a high impact of seawater intrusion, low population density (from 182 to 949 habitants per km^2) (DHATG, 2019), and high agricultural and industrial activities related to the coastal economy.

The middle zone stretching from the 30th km to the 58th km from the coastline is mainly characterized by the medium impact of seawater intrusion, high population density (from 768 to 2698 habitants per km^2) (DHATG, 2019), and high residential and industrial activities. The last zone stretching from the 58th km to the 110th km from the coastline is characterized by a low impact of seawater intrusion, low population density (from 172 to 692 habitants per km^2) (DHATG, 2019), and high agricultural activities.

The waterway types: The waterways in the current studied area were separated into two types, which are the main river (Tien river) and its tributary canals. The Tien River is the main waterway in the studied area, connecting the mainstream of the Mekong River on one end and the East Sea on the other end. The canal system is the intertwined waterways, mainly composed of small canals and short, narrow rivers, which connect local pollution sources to the Tien River. These two types of waterways are randomly distributed over the three spatial zones, making the two experimental factors for the current study.

Sampling and chemical analysis

Water sampling was carried out for 5 consecutive years from 2015 to 2019, and four sampling campaigns in March, June, September, and November each year were conducted. For each campaign, 34 samples were taken from 34 pre-selected sampling sites fixed throughout the experimental period (Fig. 1) (3 sites on the Tien River in each of three spatial zones, and 6, 7, and 12 sites on the canals in zones 1, 2, and 3, respectively), making a total of 680 (34 × 4 campaigns per year × 5 years) samples taken for the current study. A Van Dorn water sampler was used to take 8 sub-water samples for the 0–50-cm surface layer into a 40-L bucket. Finally, around 5 L of water from this bucket was further taken into a plastic bottle with a firm cap, which was immediately stored in an ice-box at 4 °C and transported to a laboratory for analysis.

The water remaining in the bucket was measured directly for pH (using a Thermo Scientific™ Orion™ 3-Star Benchtop pH Meter), temperature, electrical conductivity (EC) (using Oaklon conductivity, TDS, °C meter, Con 11 series), dissolved oxygen (DO) (using an oxi 3210 portable dissolved oxygen meter), and turbidity (using a Hach DR/2010 spectrophotometer). These parameters were shown in pH unit, °C, dS m^{-1}, mg L^{-1}, and NTU, respectively. In the laboratory, the water samples were analyzed for Cl$^-$, SO_4^{2-}, ammonium (NH_4-N), nitrate (NO_3-N), total N, total suspended solids (TSS), orthophosphate (PO_4-P), total P, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and coliform bacteria (Coliform). These measurements were conducted, following the National standard methods for drinking water quality (QCVN 01:2009/BYT, 2009) and by Nguyen et al. (2019b). In addition, Cl$^-$ concentration was measured using a titration method (Hajrasuliha et al., 1991), and SO_4^{2-} concentration was determined using the method by Rice et al. (2017). These parameters were presented in the unit of mg L^{-1}, except Coliform in MPN 100^{-1} mL.

Statistical analyses

The whole statistical process in the current study was applied in six sequential steps (Supplementary Figure 1). The first step was to do an analysis of variance (ANOVA) to examine the effects of the interaction or individuals (simple factor) of the two experimental factors on each of 16 water quality parameters. The second step was to implement multiple regression analysis 1 to estimate Pearson's correlation coefficients among 16 water parameters measured. The third step was to do principal component analysis/factor analysis (PCA/FA) to apportion pollution sources potentially contributing to degrading the water quality. The fourth one was to compute the water quality index (WQI) based on the 16 water quality parameters and the PCA/FA results, followed by ANOVA. The fifth one was to do multiple regression analysis 2 to quantify the percentage of individual pollution sources contributing to the total variance of the WQI. The last one was to compute the averaged relative content (ARC) of parameters having higher loading value (> 0.5) within individual pollution sources (varimax factors) determined from PCA/FA, followed by ANOVA.

ANOVA was carried out, following a completely randomized two-factor design. A full statistical model of ANOVA was $\gamma_{ije} = \mu + \beta_i + \propto_j + \propto \beta_{ij} + \varepsilon_{ije}$; where γ_{ije} is the response of the individual combination of the two experimental factors, μ is overall mean, β_i is the fixed effect of the ith spatial zone, α_j is the fixed effect of the jth waterway, $\beta\alpha_{ij}$ is the interactive effect of the waterway and spatial zone, and $\in_{ije}$ is the random error with mean zero and having normal distribution (Akhtar & Memon, 2009). When the ANOVA result indicated a significant effect at $P \leq 0.05$, Tukey's Honest Significant Difference test was used to differentiate the means. Principal component analysis/factor analysis (PCA/FA) was applied to the whole data to separate the pollution sources, following the procedure described by Eqani et al. (2011) and (Phung et al., 2015). The WQI for the current study was computed from the 16 water quality parameters, based on the PCA/FA results (Mukherjee & Lal, 2014) using Eq. 1.

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

where n is the number of water parameter, w_i is the weightage of the ith parameter, and s_i is the score of the ith parameter. The w_i was determined using the PCA/FA results (Table 2), and s_i is determined through equations 2 and 3. The sixteen 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 parameter includes pH, which should vary from 6 to 8.5 (MONRE, 2015), and the less-is-better include the remaining 14 parameters. For the more-is-better and the neutral parameters, s_i is determined following equation 2.

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

For the less-is-better parameters, s_i is determined following equation 3

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

where x_i, $x_{\min}$, and $x_{\max}$ are the analyzed, minimum, and maximum values of the parameter i, respectively.

The PCA/FA result was 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 > 1 were retained for weightage estimation of the water parameters having a high loading value (> 0.5) with the corresponding varimax factor. The weightage was computed following equation (4)

$$\frac{e_i}{\mathrm{Sum}} \tag{4}$$

where e_i is the eigenvalue of the varimax factor i and Sum is the sum of the eigenvalue of all varimax factors that remained after PCA/FA. The computed WQI was also subjected to statistical analyses, including two-way ANOVA and multiple linear regression analysis as mentioned below.

The multiple regression analysis was performed to quantify the percentage of the 6 varimax factors (equivalent to 6 potential pollution sources) extracted from PCA/FA contributing to the WQI (Putri et al., 2018). Finally, the ARC for individual varimax factors was computed in two sequential steps, the first of which was to standardize the values of individual water parameters based on Eq. 2 and the second one was to average the standardized values of parameters having high loading values with each of varimax factors. In addition, the longitudinal dynamics of the WQI and ARCs were examined using a scatter plot method. Statistical analyses were conducted, using JMP pro 13 (SAS Institute Inc, NC, USA). Figures were established using Sigmaplot 12 (Systat Software Inc.).

Results

The water quality as affected by experimental factors

Table 1 shows that six water parameters including pH, turbidity, EC, TSS, Cl$^-$, and SO_4^{2-} were significantly

Table 1 The values of 16 water quality parameters in two waterway types and three examined zones. Asterisk indicates the tested effect is statistically significant, and NS indicates the effect is not significant at $P < 0.05$. Note if the interactive effect is significant, the single effect of the waterway and zone is not tested. Within a raw, data attached by the same letter were not significantly different from the other

Parameter	Statistics	Tien River			Tributary canals			Statistical result		
		Zone 1	Zone 2	Zone 3	Zone 1	Zone 2	Zone 3	Interactive effect	Waterway effect	Zone effect
pH	Mean	7.08^{abc}	7.18^{abc}	7.27^{ab}	7.33^{a}	7.08^{bc}	7.03^{c}	*		
	SE	0.09	0.08	0.06	0.04	0.05	0.04			
Temperature (°C)	Mean	30.23	30.44	30.08	30.71	30.35	30.54		*	
	SE	0.23	0.16	0.14	0.15	0.14	0.09			
Turbidity (NTU)	Mean	45.2^{a}	35.1^{b}	23.2^{cd}	15.5d	26.1^{c}	19.9^{d}	*		
	SE	3.90	2.54	1.99	1.01	1.80	0.86			
EC (dS m^{-1})	Mean	0.46^{a}	0.04^{c}	0.02^{c}	0.23^{b}	0.11^{c}	0.04^{c}	*		
	SE	0.08	0.01	0.00	0.04	0.03	0.00			
DO (mg L^{-1})	Mean	4.16	4.50	4.48	3.72	3.86	3.80		*	*
	SE	0.12	0.10	0.10	0.08	0.07	0.06			
TSS (mg L^{-1})	Mean	78.8^{a}	74.1^{ab}	59.3^{b}	66.1^{ab}	59.5^{b}	69.3^{ab}	*		
	SE	5.23	5.47	3.43	3.73	2.82	2.34			
COD (mg L^{-1})	Mean	28.64	22.22	18.93	26.55	21.43	23.54			*
	SE	3.49	3.16	1.83	2.07	1.22	0.90			
BOD5 (mg L^{-1})	Mean	13.80	11.08	8.90	12.78	10.14	11.09			*
	SE	2.01	2.00	1.01	1.16	0.67	0.47			
Cl− (mg L^{-1})	Mean	1249^{a}	77.1^{c}	18.7^{c}	521.8^{b}	249^{bc}	35.8^{c}	*		
	SE	241.0	20.0	1.8	105.5	74.4	3.3			
SO42− (mg L^{-1})	Mean	254^{a}	35.0^{c}	28.2^{c}	112.8^{b}	70.8^{bc}	68.1^{bc}	*		
	SE	44.5	3.4	2.2	18.2	11.4	4.4			
NH4-N (mg L^{-1})	Mean	0.41	0.27	0.25	0.61	0.42	0.44		*	*
	SE	0.09	0.06	0.05	0.07	0.05	0.04			
NO3-N (mg L^{-1})	Mean	0.35	0.53	0.47	0.37	0.52	0.44			*
	SE	0.07	0.06	0.03	0.04	0.05	0.02			
Total N (mg L^{-1})	Mean	3.45	3.47	3.34	3.60	3.80	3.83		*	
	SE	0.17	0.16	0.19	0.14	0.14	0.12			
PO43−-P (mg L^{-1})	Mean	0.08	0.16	0.13	0.15	0.16	0.11			*
	SE	0.01	0.02	0.02	0.02	0.02	0.01			
Total P (mg L^{-1})	Mean	0.24	0.33	0.25	0.28	0.28	0.28	NS	NS	NS
	SE	0.04	0.06	0.03	0.03	0.03	0.02			
Coliform (MPN 100^{-1} mL)	Mean	1355	1380	1322	1794	1783	1897			
	SE	181	257	220	360	266	157	NS	NS	NS

affected by the interaction of the waterway type and spatial zone, while the pH of the canals in zone 1 was the highest (7.33), that of the same waterway type in zone 3 was the lowest (7.03) of the six combinations of two waterway types and three spatial zones. Turbidity was significantly highest in the Tien River in zone 1 (45.2 NTU) and lowest in the canals in zone 1 (15.5) and 3 (19.9). EC was significantly highest in the Tien River in zone 1 (0.46 dS m^{-1}) and lowest in the Tien River in zone 3 (0.02). The Tien River in zone 1 also had the highest concentration of TSS (78.8 mg L^{-1}), followed by Tien River in zone 2 (74.1), canals in zone 3 (69.3), canals in zone 1 (66.1), canals in zone 2 (59.5), and Tien River in zone 3 (59.3). The variation of the concentration of Cl^- and SO_4^{2-} in six combinations of two experimental factors was quite similar, significantly highest in the Tien River in zone 1 (1249, 254, mg L^{-1}) and lowest in the Tien River in zone 3 (18.7, 28.2), respectively. Table 1 also shows that temperature (mean = 30.39 °C), DO (mean = 3.95 mg L^{-1}), NH_4-N (mean = 0.43 mg L^{-1}), and total N (3.68 mg L^{-1}) were significantly affected by the waterway types and DO; COD (23.56 mg L^{-1}), BOD_5 (11.24 mg L^{-1}), NH_4-N, NO_3-N (0.45 mg L^{-1}), and PO_4-P (0.13 mg L^{-1}) were significantly affected by the spatial zones, while total P and coliform were not significantly affected by any experimental factors.

The WQI was significantly affected by the interaction of the waterway type and the spatial zone (Fig. 2). In both waterway types, zone 3 had significantly higher WQI (86.8 for the River and 85.2 for the canals) than zone 1 (80.2 for the River and 82.8 for the canals), but the difference in WQI between zone 3 and zone 1 was much greater in the Tien River than in the canals (Fig. 2a). In zone 1 the River was lower in WQI than the canals, while in zone 3 the River was higher in WQI than the canals. The WQI was significantly improved from the coastal side to the other side of the examined area, following an exponential model (Fig. 2b). In addition, the annual variation of 16 measured parameters and WQI was examined and shown in Supplementary Table 1. Although individual parameters varied largely, the WQI varied slightly from 81 to 86 for the five examined years.

Multivariate analysis

The PCA/FA showed that six varimax factors having an eigenvalue > 1 were extracted that together explained 69.98 % of the total variance of the whole dataset (Table 2). The most important factor (VF1), explaining 21.99 % of the total variance, had high loading values (greater than 0.5) with three parameters (Cl^-, SO_4^{2-},

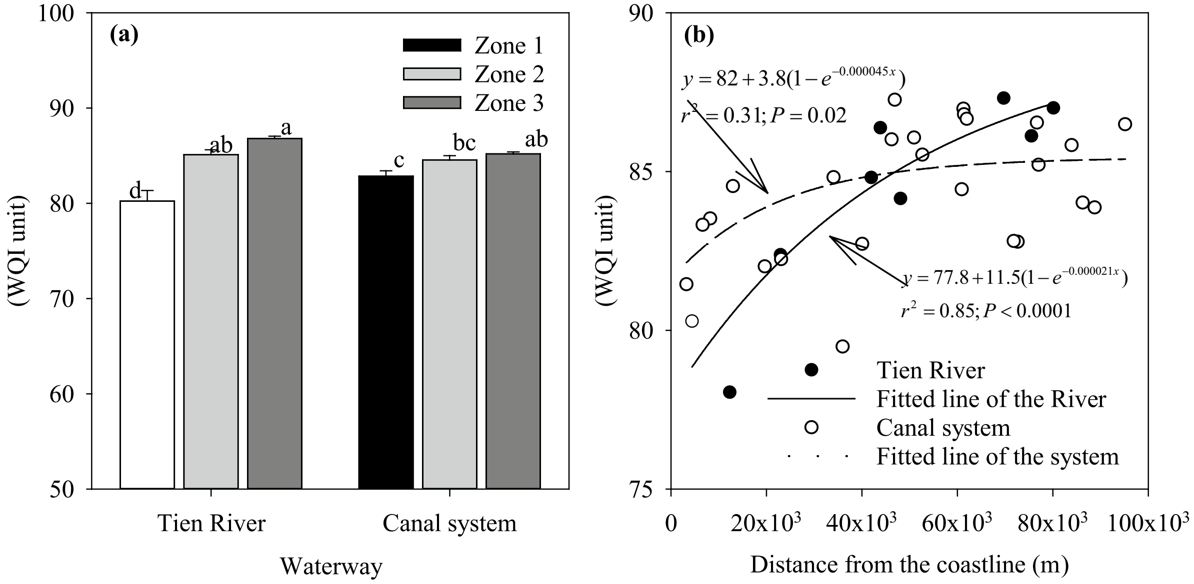

Fig. 2 Surface water quality index (WQI) as affected by the interaction of waterway types and seawater intrusion - affected zones (**a**) and longitudinal dynamics of WQI along the distance from the coastline (**b**). Within panel **a**, bars attached with the same letters are not significantly different from the other. Error bars indicate standard errors

Table 2 Loading values of 16 water quality parameters from principal component analysis/factor analysis. Bold numbers are those greater than 0.75, and underlined numbers are those greater than 0.5 and smaller than 0.75. (Note: VF: varimax factor)

Parameters	Varimax factor					
	VF1	VF2	VF3	VF4	VF5	VF6
Cl^-	**0.93**	−0.05	0.09	−0.06	0.05	−0.08
SO_4^{2-}	**0.91**	−0.04	0.19	0.08	−0.04	−0.02
EC	**0.90**	−0.04	0.25	−0.02	0.01	−0.09
Total P	−0.03	**0.88**	−0.08	−0.08	0.06	0.08
PO_4-P	−0.07	**0.87**	0.00	−0.08	0.05	0.11
Coliform	− 0.03	0.60	0.12	0.11	0.17	−0.23
DO	0.11	0.30	−0.08	−0.65	−0.24	0.19
COD	0.27	−0.05	**0.91**	−0.04	0.03	−0.04
BOD_5	0.28	0.04	**0.89**	−0.10	0.06	−0.01
Temperature	0.11	0.14	0.26	−0.05	−0.23	−0.62
NH_4-N	0.09	0.02	−0.07	**0.75**	−0.23	0.11
Total N	−0.02	0.13	−0.19	0.62	−0.09	0.51
TSS	−0.03	0.25	0.09	0.09	0.68	−0.36
Turbidity	0.08	0.27	−0.15	−0.05	0.64	0.19
pH	−0.02	−0.16	0.22	−0.35	0.55	0.12
NO_3-N	−0.10	0.13	0.30	0.04	−0.11	0.56
Eigenvalue	3.52	2.36	1.75	1.26	1.21	1.10
% total variance	21.99	14.75	10.94	7.89	7.54	6.88
Cumulative percentage variance	21.99	36.73	47.67	55.56	63.10	69.98
Weightage	0.10	0.07	0.08	0.04	0.04	0.05

and EC). The second most important factor (VF2), explaining 14.75 % of the total variance, had high correlation coefficients with three parameters, including total P, PO_4-P, and coliform. Similarly, factor 3, explaining 10.94% of the total variance, had a strong relationship with COD and BOD_5. Other factors 4, 5, and 6 explaining 7.98, 7.54, and 6.88 % of total variance had a strong relationship with three parameters each.

Multiple regression analysis showed that the WQI was significantly correlated with all six extracted factors, of which varimax factor 1 explained 48.98 %, factor 2 explained 16.29 %, factor 3 explained 24.63 %, and the other factors 4, 5, and 6 explained 2.18, 5.17, and 0.15 % of the total variance of the WQI (Table 3). The six factors together explained 97.16 % of the total variance of WQI.

Averaged relative content within individual varimax factors

The ARC computed from SO_4^{2-}, Cl^-, and EC for varimax factor 1 was significantly affected by the interaction of the two experimental factors (Fig. 3a). The Tien River in zone 1 had the highest ARC (0.17), followed

Table 3 Percentage of individual varimax factors (VF) from PCA/FA in explaining the total variance of WQI of the studied area. Prob < 0.05 indicates the effect of the considered factor is significant

Source	Sum of squares	Contribution (%)	Prob > *F*	Important parameters
Factor 1	8935.25	48.89	< 0.0001	Cl^-, SO_4^{2-}, EC
Factor 2	2977.77	16.29	< 0.0001	Total P, PO_4-P, coliform
Factor 3	4501.91	24.63	< 0.0001	COD, BOD_5
Factor 4	398.44	2.18	< 0.0001	NH_4-N, total N, DO
Factor 5	944.75	5.17	< 0.0001	TSS, Turbidity, pH
Factor 6	27.80	0.15	< 0.0001	Temperature, total N, NO_3-N
Error	535.33	2.84		
Total variance	18,848.47	100.00		

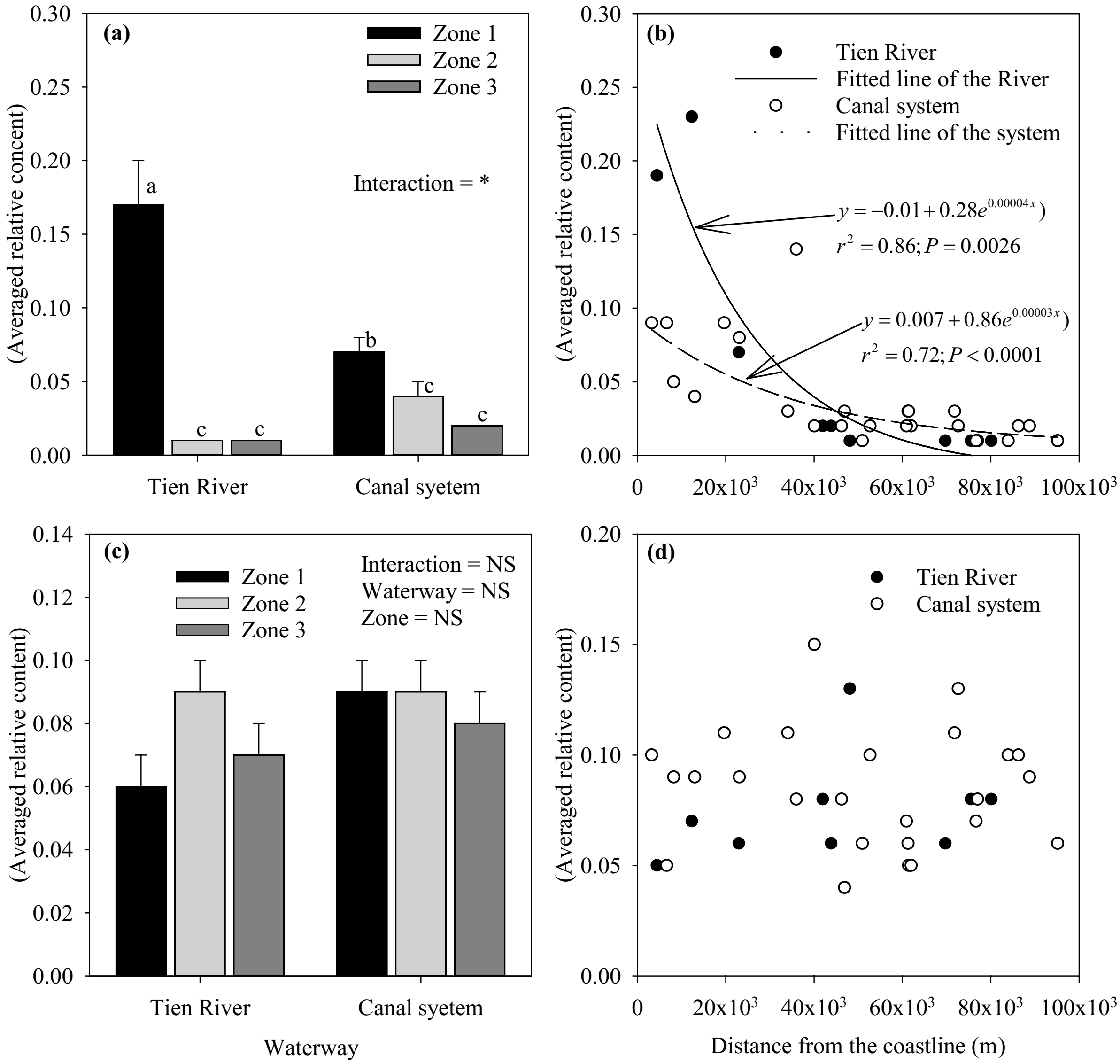

Fig. 3 Averaged relative content (ARC) of parameters having high loading value (> 0.5) with VF1 (SO_4^{2-}, Cl^-, and EC) (**a** and **b**) and VF2 (total P, PO_4^{3-}-P, and coliform) (**c** and **d**), as affected by waterway type and spatial zone (**a** and **c**) and the longitudinal dynamics of ARC along the distance from the coastline (**b** and **d**). For panel **a**, bars attached with the same letter were not significantly different from the other. Error bars indicated standard error. Note: only a significant relationship was shown with the equation, r^2 (coefficient of determination), and probability

by the canals in zone 1 (0.07), and the other four combinations. This ARC of the River was decreased from the coastline to the other end much more rapidly, compared to that in the canals (Fig. 3b). The varimax factor-2 ARC was not affected by the experimental factors, varying from 0.61 to 0.91 (Fig. 3c, d). The ARC related to the varimax factor 3 was not affected by the interaction and by the River but by the spatial zone, of which zone 1 had the ARC (0.13) significantly higher than the other zones (0.1 for the zones 2 and 3) (Fig. 4a). This varimax factor was decreased significantly from the coastline to the other end for the river but not for the canals (Fig. 4b). Similar to factor 2, the ARC of factors 4 and 6 was not affected by any experimental factor, varying from 0.28–0.30 with a mean of 0.29 for factor 4 (Fig. 4c, d) and from 0.32

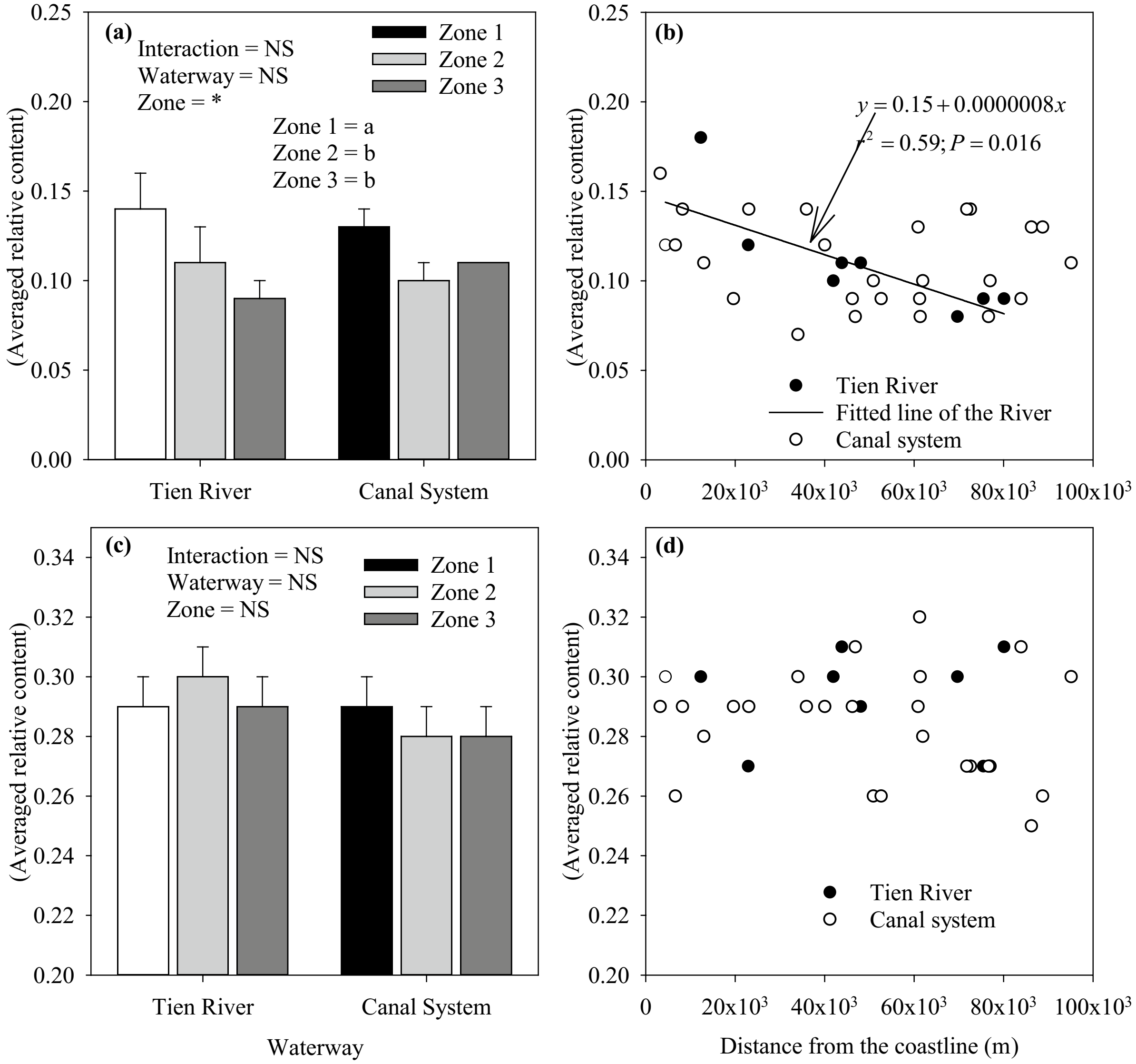

Fig. 4 Averaged relative content (ARC) of parameters having high loading value (> 0.5) with VF3 (COD and BOD_5) (**a** and **b**) and VF4 (NH_4-N, total N, DO) (**c** and **d**) as affected by waterway types and spatial zone (**a** and **c**) and the longitudinal dynamics of ARC along the distance from the coastline (**b** and **d**). For panel **a**, bar attached with the same letter was not significantly different from the other. Error bars indicated standard error. Only the significant relationship was shown with the equation, r^2 (coefficient of determination), and probability

to 0.36 with a mean of 0.34 for factor 6 (Fig. 5c, d). The ARC of factor 5, averaged over TSS, turbidity, and pH was significantly affected by the interaction of the waterway types and spatial zones (Fig. 5a, b). For the Tien River, zones 1 and 2 had significantly higher ARC than zone 3, while for the canals, three spatial zones were not significantly different from each other in ARC. The spatial variation of the ARC along the distance from the coastline was not significant with any waterway types.

Combined results for the studied area

To summarize the results from the above sections, a synthetic graph was formulated (Fig. 6). The surface water quality was relatively poor in the downstream

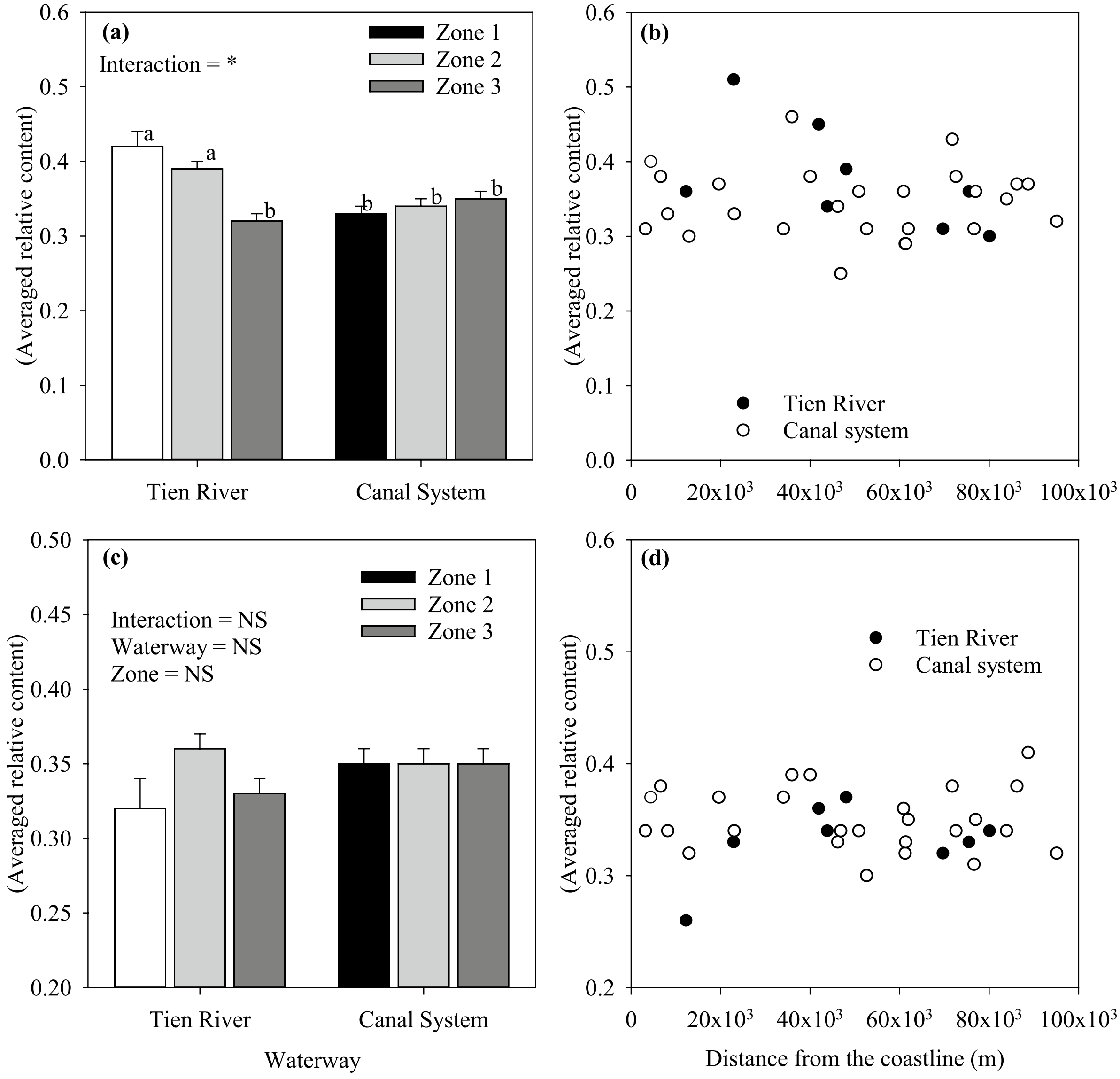

Fig. 5 Averaged relative content (ARC) of parameters having high loading value (> 0.5) with VF5 (TSS, Turbidity, pH) (**a** and **b**) and VF6 (temperature, NO_3-N) (**c** and **d**) as affected by waterway type and spatial zone (**a** and **c**) and the longitudinal dynamics of ARC along the distance from the coastline (**b** and **d**). For panel **b**, bars attached with the same letter were not significantly different from the other. Error bars indicated standard error. Only the significant relationship was shown with the equation, r^2 (coefficient of determination), and probability

zone connecting to the sea and rapidly got better to the upstream zone with a faster increase rate found in the Tien River and a slower improving rate in the canals. Zone 1 could be affected by the seawater intrusion (explaining around 49% of the total variance of the WQI). One important feature could be found from Fig. 6 that zone 2 had a higher population density than the other zones. Residential activities could be one important pollution source mainly derived from zone 2, explaining around 16 to 40% of the total variance of the WQI. Zone 3 having high water quality in both waterways could be polluted with a mixture of various pollution sources, which together explained around 16 to 23% of the total variance of the WQI.

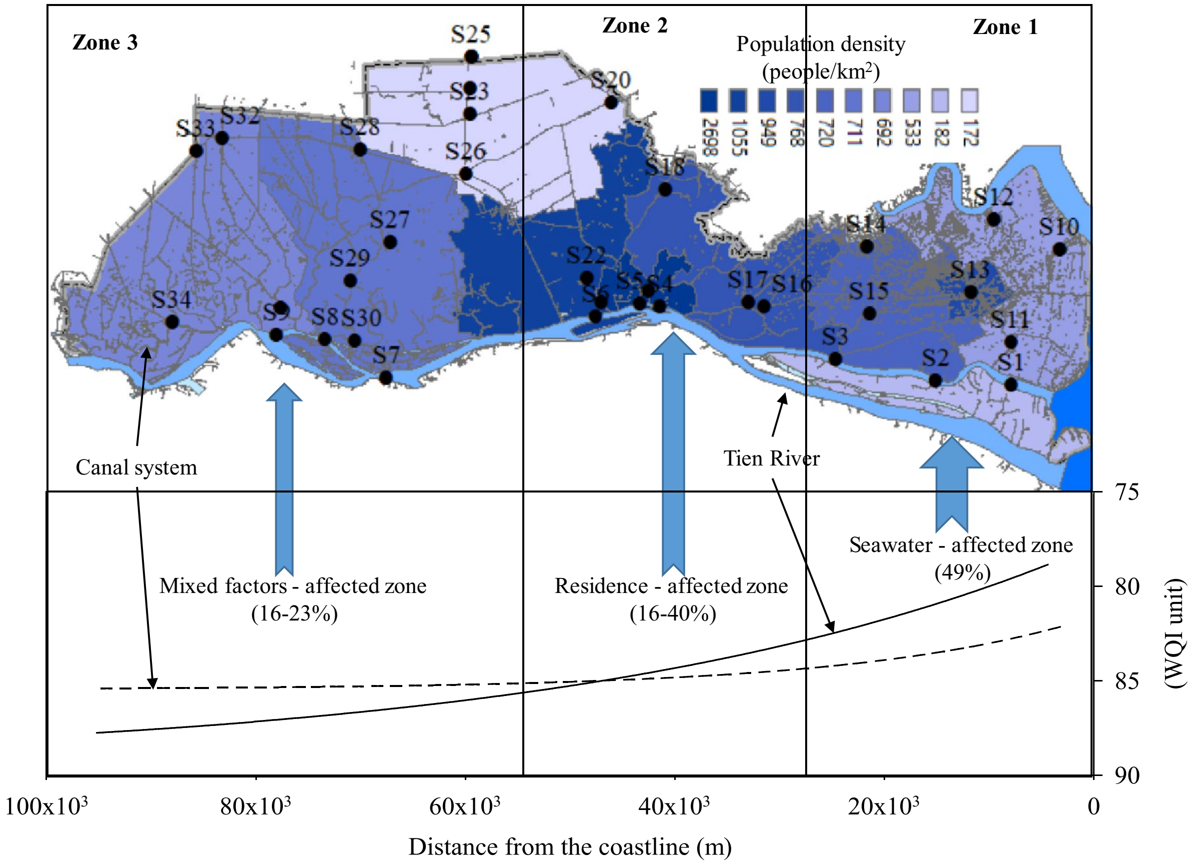

Fig. 6 Synthetic graph showing the spatial variation of water quality of both the Tien River and its tributary canals in three zones with various pollution sources

Discussion

The pollution sources for surface water in the current study

Six important varimax factors were extracted from PCA/FA (Table 2), indicating that at least six important pollution sources could contribute to degrading the water quality of the studied area. The most important sources, represented by Cl^-, SO_4^{2-}, and EC could be derived from the seawater, which brought salty ions to the study area. The significant correlation coefficient among these three parameters (Supplementary Table 2) indicated that these ions could be derived from a similar source. The current study was based on a coastal area, connected to the sea through the Tien River and many small tributaries, which bring these elements to the study area's waterways by seawater invasion. Likewise, Alfarrah and Walraevens (2018) found that the seawater intrusion was the main reason for increasing the values of some parameters including EC, SO_4^{2-}, and Cl^- of underground water in North West Libya. Ahmed and Askri (2016) demonstrated that the increased concentration of Cl^- and SO_4^{2-} of groundwater in the Northwest Coast of Oman was due to seawater intrusion. Consequently, the averaged relative content (ARC) of these parameters (Table 1) was significantly higher in the areas connecting to the sea (Fig. 3a, b) and lower in the inland areas far from the sea. The rapid decrease in the ARC along the distance inwards the inland from the coastline led to negligible effects of the seawater intrusion at the inland distance of around 60 to 80 km from the sea.

Three parameters of total P, PO_4-P, and coliform were significantly correlated with each other (Supplementary Table 1) and also had high loading values with varimax factor 2 (Table 2). These indicate that these three pollutants could come from a similar pollution source, related to the residential or agricultural activities, which may release a large amount of phosphorous into environments (Bowes et al., 2015). Sewage discharged from residential areas (domestic wastewater) was mainly composed of waters flowing from bathrooms, kitchens, and toilets, characterized by a high content of phosphorous compounds (Butler et al., 1995; Kok et al., 2018). The application of P fertilizers for better agricultural productivity and surface run-off (Bertol et al., 2010) could be the case to release P to the waterways in the current study. On average, the middle zone, having higher population density (Fig. 6), tended to have a higher ARC for factor 2 than the other two end zones (Fig. 3a, b), suggesting that P discharged from residential areas could be stronger than from agricultural zones. In addition, coliform, also an important parameter in this pollution source, was more likely derived from the residential area, which discharged wastewater characterized by a high concentration of E.coli and coliform (Oteng-Peprah et al., 2018; Sunta et al., 2019). These suggested that the second pollution sources related to P content and coliform could more likely be involved in residential activities in the current study.

Having high correlation coefficients with COD and BOD_5 (these two parameters also significantly correlated with each other (Supplementary Table 1)), the varimax factor 3 may suggests that other main pollution sources for the study area could be related to organic matter. A significant decrease in ARC of COD and BOD_5 for the Tien River from the downstream to upstream zones (Fig. 4b) may indicate that organic matter could be transferred from the upper parts to the lower part of the River. These transport effects may not be seen in the canals because they were intertwined and the water may not flow through the canals as seen in the case of the Tien River. Several anthropogenic activities could emit a large amount of organic matter into environments, such as agricultural activities of applying organic fertilizer (Li et al., 2017) and/or residential activities, which may discharge a large amount of domestic sewage, oil and grease, and solid wastes into surface-water bodies (Huang et al., 2010). The high population density in the middle zone while more agricultural activities in the other two end zones may contribute to enriching the organic pollutants in the River equally over the three spatial zones (Fig. 4b).

The other two main pollution sources for the surface water in the current study could be related to NH_4-N, total N, and DO for varimax factor 4 and total N, NO_3-N, and temperature for varimax factor 6. These sources could be likely related to nitrogen, which can be biologically transformed in water following multiple processes of oxidation and reduction (Xia et al., 2018), determined by dissolved oxygen status and temperature of the environment (de Almeida Fernandes et al., 2018; Hong et al., 2019). This indicated that these parameters had a strong relationship with each other, as found in the current study. Nevertheless, major pollution sources for these two factors could be unclear because ARCs in all 6 combinations (2 waterway types × 3 spatial zones) under factor 4 (Fig. 4c, d) and factor 6 (Fig. 6c, d) were similar. Nitrogen concentration in surface water could be derived from various sources, such as atmospheric deposition, dust in rainwater, agricultural wastes, domestic wastewater, industrial wastewater (Maghanga et al., 2013; Noukeu et al., 2016; Xue et al., 2016). Moreover, aquaculture with feed residue may enrich the nitrogen concentration in surface water (Dauda et al., 2019).

The last pollution source could be involved in TSS, turbidity, and pH, which had high loading values with the varimax factor 5. While the ARC for this factor of the River was significantly different among the three spatial zones (higher in zone 1 and lower in zone 3), that of the canals was not significantly different (Fig. 5a), indicating that anthropogenic activities on the River, such as aquaculture and cargo ship activities, could be the main pollution sources. Aquaculture such as Pangasius catfish culture was commonly carried out in the Mekong River system in Vietnam and Tien River (Nguyen et al., 2019a). Uneaten feed, feces, and metabolic wastes from aquaculture may pollute the river water with a high content of suspended solids (Coldebella et al., 2017; Dauda et al., 2019). Re-suspension of sediment from the riverine bottom due to the activity of cargo ships could be another season of increasing ARC of TSS, turbidity, and pH along the River.

Longitudinal dynamics of the water quality

An important trend in the current study was a decline in WQI from the upstream zone to the downstream zone, which is connected to the sea (Fig. 6). Reasons for the trend could be related to the pollution sources and transport of pollutants from the upper to the lower parts of the Tien River, polluting the lower parts (more discussion in the following section). This decreasing trend was similar to the other rivers such as the Saigon River (Nguyen et al., 2011), the Beheshtabad River, Iran (Fathi et al., 2018), the Cau River, Vietnam (Cao et al., 2020), the Talar River, Iran (Darvishi et al., 2016), and the Suceava River, Romania (Briciu et al., 2020). Nevertheless, this decreasing trend was not always true from other studies. For example, Tian et al. (2019) showed that the WQI in the Mun River in Thailand tended to be low in the upstream sites and high in the downstream sites and this variation was attributed to the difference in non-point source pollution varying over the 800-km length of the studied river. Because of its length, polluted water from the upper part of the Mun River may not contribute to decreasing water quality in the lower parts due to the natural self-purification of rivers (Kuriata-Potasznik et al., 2016), leading to higher water quality in the lower reaches than the upper reaches of the River.

Assessment of water quality as affected by waterway types and spatial zones

For the downstream zone, the WQI of the Tien River was significantly lower than that of the canals, while for the upstream zone the WQI of the River was significantly higher than that of the canals (Figs. 2a, b and 6). This interaction was in line with our hypothesis but was limitedly reported in the literature. For the current study, it can be explained by several reasons. The first one could be related to pollution sources 1 and 5. While pollution source 1 was involved in the seawater intrusion, bringing salty ions to the River starting from the estuary, pollution source 5 was more related to the aquaculture activities resulting in lower water quality in the downstream than in the upstream zones of the River. The second reason could be involved in the movement of the pollutants from their sources through the three zones of the canals and the River by hydrological currents. As the river was a main waterway in the studied area, the pollutant movement could be stronger through the River than through the canals, leading to more pollution of water in the downstream zone than in the upstream zone of the River, relative to the canals. In brief, the movement of the pollutants from the canals, where received the pollutants from their sources to the River, and the subsequent transport of these pollutants from upper parts to lower parts through the river current could be the main reason to explain this interaction. The transport of pollutants from the upstream catchment or two riversides was identified as one of the important reasons for lowering the water quality in downstream reaches of various Rivers (Babić et al., 2019; Cao et al., 2020; Nguyen et al., 2020; Nguyen et al., 2011). These indicated that water flows such as in and out currents played an important role in modifying the effects of pollution sources on the water quality of rivers and canals connecting to the main river. In short, two natural and anthropogenic factors, which were water flow (determined by waterway types) and pollution sources (reflected through spatial distribution), occurring on the Tien River and its tributary canals could be the principal reasons controlling the statue of surface water quality in the current study.

Conclusions

The surface water quality got better from the downstream to the upstream zones and the improving rate of water quality was faster in the River than in the canals. The surface water was potentially influenced by six main pollutant sources, one of which was derived from the seawater intrusion, one from aquaculture mainly happening on the River, and the others from agricultural and residential as well as industrial activities mainly occurring surrounding the canals. The polluting effects of these sources could be modified by water transportation, interactively determining the inland surface water quality in a coastal area. These indicated that the surface water quality varied greatly with waterway types and seawater intrusion-affected zones, which were determined based on the distance from the coastline.

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Declarations

Conflict of interest The authors declare no competing interests.

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