Environ Monit Assess (2023) 195:408
https://doi.org/10.1007/s10661-023-11026-x

Spatial and temporal analysis and quantification of pollution sources of the surface water quality in a coastal province in Vietnam

Thang Viet Le · Duong Thuy Phuc Nguyen · Binh Thanh Nguyen

Received: 1 August 2022 / Accepted: 13 February 2023

Abstract The surface water quality in coastal areas may be highly vulnerable to degradation due to various pollution sources such as seawater intrusion and anthropogenic activities. The current study sought to spatially and temporally analyze and quantify pollution sources of the surface water system in the coastal province of Tra Vinh, Vietnam. A total of 600 surface water samples were taken from 30 monitoring sites distributed over 4 spatial zones. Water samples were collected in four campaigns each year during the dry and rainy seasons from 2016 to 2020 and analyzed for 10 physiochemical and biological parameters. The analyzed data were calculated for the water quality index (WQI). Two-way analysis of variance, principal component analysis/factor analysis (PCA/FA), and multivariable regression analysis (MRA) were conducted over the whole dataset. The results showed that the WQI decreased from the inland zone to the coastal area, was greater in the river zone than in the canal zone, and was higher in the dry season than in the rainy season. The PCA/FA revealed that surface water quality was affected by at least 4 main pollution sources, including agricultural production, seawater intrusion, residential activities, and mixed sources. MRA revealed that these pollution sources explained 68.3%, 12.8%, 7.0%, and 2.7% of the total variance of the WQI, respectively. In summary, the surface water quality in the study area significantly changed spatially and temporally, depending on four pollution sources, which need to be managed properly for a better environment and sustainable development.

Keywords Anthropogenic influences · Coastal area · Multivariate statistical analysis · Pollution sources · Water quality

Introduction

Surface water resource plays an important role in ensuring global sustainable development goals. Its quantity and quality should be conserved and improved because of the increasing pressures from economic and societal development as well as global climate change (Mateo-Sagasta et al., 2018; Okello et al., 2015). The surface water quality of a particular area can be deteriorated by numerous pollution sources. In the context of global climate change as reported recently (IPCC, 2019), the quality of a surface water system of a coastal area could be influenced by some typical pollution sources, including anthropogenic activities (agricultural production,

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10661-023-11026-x.

T. V. Le · D. T. P. Nguyen · B. T. Nguyen (✉)
Institute of Environmental Science, Engineering, and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Viet Nam
e-mail: nguyenbinh@iuh.edu.vn

Published online: 17 February 2023

residential activities, and industrial production) and seawater intrusion. While the surface water quality of sea-connected areas can be more influenced by the seawater intrusion, that in the inland areas may be controlled by anthropogenic activities. The quality of the surface water can also vary with seasons, which is involved in the hydrological regime occurring in the coastal area. Those indicate that the surface water quality can vary in space and time, which requires more studies. Furthermore, primary pollution sources in coastal areas should be analyzed and quantified to develop appropriate management strategies and efficient pollution treatment (Behmel et al., 2016; Giri et al., 2020; Tirkey et al., 2013). The multivariate analysis method such as principal component analysis/factor analysis (PCA/FA) can be used to separate and quantify the contribution of individual pollution sources to degrading the water quality (Ibrahim et al., 2021; Oketola et al., 2013; Yang et al., 2021). These findings indicate that many pollution sources can contribute to the degradation of the surface water quality, which is needed to be analyzed and quantified for better management.

Tra Vinh is a coastal province, located in the lower reaches of the Mekong River in southern Vietnam, between the Co Chien River (a tributary of the Tien River) and the Hau River, which runs into the East Sea (Fig. 1). The rapid socio-economic development of Tra Vinh province in recent years has generated a considerable quantity of untreated wastewater discharged into water bodies, degrading its quality. Many anthropogenic factors, such as industrial production, aquaculture, agricultural production, residential activities, and natural factors (runoff water and seawater intrusion) may pollute surface-water bodies in the province (DonRe, 2020). These pollution sources distribute differently in terms of spatial and temporal aspects. In terms of spatial distribution, the coastal area could be highly affected by seawater intrusion, in addition to the other pollution sources

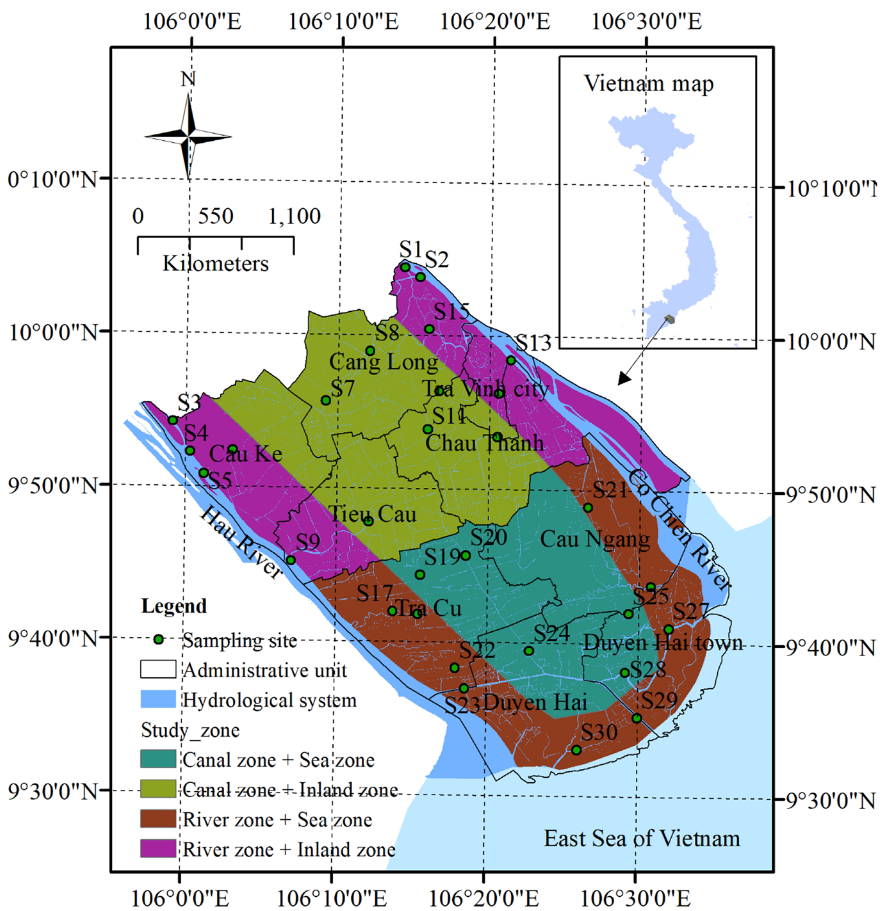

Fig. 1 Map of the study area and sampling sites of Tra Vinh province, Vietnam

such as agricultural, aquaculture, and residential activities. Meanwhile, the inland areas may be influenced by some pollution sources, such as industrial and agricultural activities, social services, aquaculture, and residential activities. The influence of these pollution sources can be altered by strong seasonal fluctuations, which are in need to study.

To protect the surface water resource for serving social-economic development, the coastal province of Tra Vinh needs to control these potential pollution sources effectively. Accordingly, it is important to determine the main pollution sources for the development of feasible and effective solutions to conserve and protect its surface-water system. The current study aimed to spatially and temporally analyze and quantify pollution sources of the surface water system in the coastal province of Tra Vinh, Vietnam. It is hypothesized that the surface water quality would be worse in the regions close to the coastline and some key pollution sources such as seawater intrusion, agricultural production, and residential activities would contribute to the deterioration of the surface-water quality in the coastal area.

Materials and methods

Study area

The current study was conducted in Tra Vinh province, which is located in the coastal area of the Mekong River delta region at 9° 31′ 5''–10° 04′ 5'' N and 105° 57′1 6''–106° 36′ 04'' E in southwestern Vietnam (Fig. 1). The province has a total coastline of 65 km, a total area of 2,390 km^2, and a population of 1,009,322 people. The average population density is about 422 people per km^2. The province contains nine administrative units, divided into two major areas which are the inland area (one provincial city and four districts) and the coastal area (one town and three districts) (Fig. 1). The population density of the inland area varies from 475 to 1,660 inhabitants per square kilometer, while the population density of the coastal area ranges from 275 to 461 inhabitants per square kilometer (DonRe, 2020). The socio-economic development conditions, the community's livelihood, the use and exploitation of water, and the discharge of pollutants into the water bodies may vary from inland region to coastal region.

Tra Vinh province lies in a subtropical monsoon climatic region which is suitable for agricultural development. The average annual temperature of the province varies from 27.2 to 27.4 °C and the annual rainfall ranges from 1,602 mm to 2,384 mm. The province has two distinct seasons, which are the rainy and dry seasons. The province has an interlaced network of rivers and canals with a total length of 578 km and 1,876 km of tributary canals, creating a complicated waterway system throughout the province (both inland and coastal areas). The system helps to irrigate the farmland in dry seasons and drain it out in the rainy seasons. The drainage system is linked to the Co Chien and Hau Rivers, which are around 45-km and 55-km long, respectively (DonRe, 2020).

Experimental factors and design

With a position in the lower reaches of the Mekong River and surrounded by the Hau and Tien (Co Chien) rivers, Tra Vinh province has a surface water system governed by human-related activities (socio-economic, community livelihood) and natural factors (runoff water and seawater intrusion) (DonRe, 2020). Anthropogenic and natural factors have different effects on surface water quality in the study area, depending on spatial position and temporal variation.

For the spatial distribution, the quality of the surface-water system in the study area could vary with the sea-related zone and waterway-related zone. While water bodies located inside the sea zone (areas near the coastline) could be strongly affected by the seawater intrusion, those situated in the inland area (areas far from the sea) could be lesser influenced (Fig. 1). The waterway-related zone may include the areas along the Co Chien and Hau Rivers that border Tra Vinh province and areas inside the province that are influenced by the interlaced-canal network. The waterway network extends over the whole study area, linking pollution sources from inside the province to the main waterways (the Co Chien and Hau Rivers) and ultimately to the sea. Therefore, the study area was artificially and spatially divided into 4 spatial experimental zones, including zone 1 (canal zone in the sea zone), zone 2 (canal zone in the inland zone), zone 3 (river zone in the sea zone), and zone 4 (river zone in the inland zone), formed from two cross spatial factors of the sea-related zone and the waterway -related zone. Furthermore, the water quality of the study area could be influenced by seasonal variation, which is another experimental factor of the current study. To collect surface water samples for chemical analysis, 30 surface-water sites were pre-selected over the four experimental zones (Fig. 1). Zones 1, 2, 3, and 4 included 5, 6, 9, and 10 sites, respectively. Sampling was conducted in both the dry and rainy seasons. Therefore, the current study was set up as a completely randomized design, with 3 experimental factors (sea-related factors and waterway-related factors, and seasonal factors) and varying replicates.

Water sampling and chemical analysis

Surface water from the 30 pre-selected sites was taken for chemical analysis in the last 5 years, from 2016 to 2020. Five sampling sites in zone 1 included S19, S20, S24, S25, and S28; Six sampling sites in zone 2 were S7, S8, S10, S11, S14, and S16; Nine sampling sites in zone 3 included S17, S18, S21, S22, S23, S26, S27, S29, and S30, and ten sampling sites in zone 4 included S1, S2, S3, S4, S5, S6, S9, S12, S13, and S15. Four sampling campaigns in March and June for the dry season and in September and November for the rainy season were carried out each sampling year. Therefore, water sampling was conducted over 5 years, four campaigns/year, and from 30 sampling sites, making a total number of 600 water samples collected for the current study.

In each water sampling campaign, the Van Dorn water sampler was used to take 8 water samples in the surface layer from 0 to 50 cm into a 100-L plastic bucket. After being mixed well, water from the bucket was representatively taken into a 5-l plastic container with a tight-fitting lid, which was placed in the 4 °C-ice box. The 30 containers from 30 sampling sites were immediately brought to the laboratory for chemical analysis of 10 water quality parameters, including pH, DO (dissolved oxygen), Cl^-, total inorganic nitrogen (TIN), total suspended solids (TSS), phosphorous (P), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total coliform, and oil and grease. These water parameters were selected to measure for the current study because they could form a minimal dataset, which can be used to identify, fractionate, and quantify the contribution of main pollution sources, which could be presumably agricultural production (TIN including NO_3^-, NO_2^-, and NH_4^+) and P, residential activities (COD, BOD_5, DO, coliform, and oil and grease), and seawater intrusion (Cl^-). pH and TSS could be derived from any pollution sources such as agricultural production and residential activities.

The pH and DO parameters were measured directly at water sampling sites. More specifically, the pH parameter was measured using the Thermo Scientific™ Orion™ 3-Star Benchtop pH meter, and the DO parameter was determined using the 3210 portable dissolved oxygen meter. Other parameters such as Cl^-, TIN including NH_4^+-N, NO_2-N, NO_3-N, TSS, P, BOD_5, COD, total coliform, and oil and grease were determined in laboratories. These analyses were conducted according to the national standard QCVN 08-MT:2015/BTNMT (Monre, 2015) and by Nguyen et al. (2019). The Cl^- concentration was measured using a titration method (Hajrasuliha et al., 1991).

Statistical analysis

The statistical analysis process in this study includes 4 consecutive steps as follows. The first step was to distinguish the pollutant sources using the principal component analysis/factor analysis (PCA/FA) on the complete dataset. The second step was to compute the water quality index (WQI) for assessment. The next step was to implement a two-way analysis of variance (ANOVA) to compare the water parameter means of the four spatial experimental zones. The last step was to conduct a multivariable regression analysis to quantify the contributive percentage of different pollution sources on WQI.

The PCA/FA was applied to the whole dataset to differentiate pollution sources according to the procedure in previous studies (Eqani et al., 2011; Phung et al., 2015). The Kaiser–Meyer–Olkin (KMO) and Bartlett's test of sphericity were conducted to determine the dataset's suitability for PCA/FA (Banda & Kumarasamy, 2020) before performing PCA/FA. Results from these two tests (an overall KMO value of 0.59 and Bartlett's significance level of less than 0.0001) indicated that the entire dataset in the current study was suitable for PCA/FA. The PCA/FA was applied in some studies conducted in Vietnam (Pham et al., 2017; Thanh Giao et al., 2021). The WQI was calculated from 10 water quality parameters based on the results of PCA/FA (Mukherjee & Lal, 2014), according to Eq. 1. The PCA/FA method was used to compute WQI because this method used a flexible set of water parameters, which fit better with the dataset measured in the current study.

$$WQI = \sum_{i=1}^{n} w_i s_i \quad (1)$$

where n is the number of water quality parameters; w_i is the weightage of the ith parameter, and s_i is the score of the ith parameter. The values of w_i were determined according to the result of the PCA/FA (Table 3) and s_i was the standardized value of all measured values of the 10 water quality parameters and was determined by Eqs. 2 and 3. Ten water quality parameters were divided into three groups, including "the more the better," "the less the better," and "neutral." The "the more the better" group includes only the DO parameter; the "neutral" group included pH, with values ranging from 5.5 to 9 (Monre, 2015), and the "the less the better" group included the 8 remaining parameters. For the "the more the better" and "neutral" parameters, the value of s_i was calculated according to Eq. 2.

$$S_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (2)$$

For the "the less the better" parameters, s_i was determined following Eq. 3.

$$S_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \quad (3)$$

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

Two-way analysis of variance (ANOVA) was performed following a statistical procedure of a completely randomized design with two experimental factors, which were the sea-related zone (sea zone and inland zone) and waterway-related zone (river zone and canal zone). The full statistical model of the ANOVA was γijе = μ + βi + αj + αβij + εije; where γije was the response of the individual combination of the two experimental factors; μ was the overall mean of the whole dataset; αj was the fixed effect of the jth sea-related zone; βi was the fixed effect of the ith waterway-related zone; αβij is the interaction effect of the two experimental factors; εije is a random error with a mean zero and having a normal distribution (Akhtar & Memon, 2009). If ANOVA results showed a significant effect with $P \leq 0.05$, Tukey's Honest Significant Difference test was used to classify the mean values. The multivariable regression analysis was performed to determine the percentage of 4 water quality factors (corresponding to 4 potential pollution sources) extracted from PCA/FA that contributed to the WQI (Putri et al., 2018). Statistical analyzes were performed using the JMP pro 16 program (SAS Institute Inc, NC, USA). Al plots were established by running Sigmaplot 12 software (Systat Software Inc.).

Results

Principle component analysis/factor analysis (PCA/FA)

Averaged values and standard deviation of the 10 measured water parameters were shown in Table 1. The mean values of 10 water parameters over four spatial zones and five examined years were also shown in Supplementary Table 1. The whole dataset was subjected to PCA/FA and the results showed that the whole dataset of surface water quality for the period 2016–2020 in Tra Vinh province could

Table 1 Averaged values and standard deviation (SD) of 10 measured water parameters. *TIN* total inorganic nitrogen

Parameters	Unit	Mean	SD	Methods
pH	N/A	7.06	0.35	pH meter
DO	mg l^{-1}	1511.40	3398.88	Dissolved oxygen Meter
Cl^-	mg l^{-1}	4.10	0.98	(Hajrasuliha et al., 1991)
TIN	mg l^{-1}	0.88	0.89	(Monre, 2015)
BOD_5	mg l^{-1}	7.03	2.71	
COD	mg l^{-1}	24.81	13.80	
TSS	mg l^{-1}	57.39	49.85	
P	mg l^{-1}	0.09	0.09	
Coliform	MPN 100 ml^{-1}	153,229.53	498,128.84	
Oil and grease	mg l^{-1}	0.41	0.27	

be divided into 4 main factors with loading greater than 1 (Table 2). The four factors together explained 62.4% of the total variance of the dataset. The most important factor (Factor 1) accounted for 20.92% of the total variance, followed by factors 2 (17.04%), factor 3 (14.01%), and factor 4 (10.43%). The first factor had a high loading value with TIN (total inorganic nitrogen), COD, P, and DO. The second factor exhibited a strong correlation coefficient with 3 parameters, which were Cl^-, pH, log(coliform). Similarly, the 3rd factor was shown to be significantly correlated with 2 parameters of BOD5 and total oil and grease. Finally, the 4th factor (Factor 4) had a significant loading value with TSS.

Surface water quality index

The water quality index (WQI) in the study area varied substantially, depending on locations and year of observation year (Fig. 2). In the inland zone, the river zone had a significantly higher WQI (0.72) than the canal zone (0.68), and in the sea zone, the river zone also exhibited a greater WQI (0.67) than the canal zone (0.66) (Fig. 2a). From 2016 to 2020, WQI was similar between the dry and rainy seasons with the exception of 2018, which showed a greater WQI in the dry season than in the rainy season (Fig. 2b).

Water quality parameters of the four PCA/FA factors

PCA/FA analysis showed that the ten measured water quality parameters could be classified into four factors (Table 2) with different values. Four water quality parameters, TIN, COD, P, and DO having high leading values with factor 1 were shown in Fig. 3. In the sea zone, the TIN value in the canal zone (1.42 mg L^{-1}) was substantially greater than that in the river zone (1.08 mg L^{-1}), and in the inland zone, the TIN value was still significantly higher in the canal zone (0.92 mg L^{-1}) than in the river zone (0.62 mg L^{-1}) (Fig. 3a). A similar situation was found for the COD parameter (Fig. 3b), which showed that water samples collected within the sea zone and canal zone had the highest COD value (36.41 mg L^{-1}), and the those collected in the inland zone and river zone had the lowest COD (17.14 mg L^{-1}). The inland zone and canal zone had the greatest P concentration (0.12 mg L^{-1}) while the sea zone and river zone had the lowest (0.07 mg L^{-1}) (Fig. 3c). Figure 3d showed that the DO parameter in the inland zone was much higher in the river zone (4.3 mg L^{-1}) than in the canal zone (3.57 3 g L^{-1}) while in the sea zone, the DO value was similar in the river and canal zones.

Three parameters, Cl^-, pH, and log(coliform) having a strong correlation coefficient with factor 2, and one parameter, TSS having a high loading value with factor 4 were shown in Fig. 4. The Cl^- concentration

Table 2 Loading values of 10 water quality parameters from principal component analysis/factor analysis. Bold numbers are greater than 0.5

Parameters	Factor 1	Factor 2	Factor 3	Factor 4	Parameter weightage
TIN	**0.79**	−0.03	0.07	−0.16	0.13
COD	**0.68**	0.42	0.34	0.16	0.13
P	**0.53**	−0.32	−0.03	0.09	0.13
Cl^-	−0.06	**0.79**	−0.02	0.25	0.10
pH	−0.08	**0.59**	0.21	−0.46	0.10
BOD_5	0.25	−0.04	**0.77**	0.23	0.06
Oil and grease	−0.16	−0.11	**0.71**	−0.15	0.06
DO	**−0.58**	0.25	0.33	0.23	0.13
Log(coliform)	0.12	**−0.69**	0.29	−0.01	0.10
TSS	−0.12	0.11	0.07	**0.81**	0.06
Eigenvalue	2.09	1.70	1.04	1.04	
Percent	20.92	17.04	14.01	10.43	
Cum Percent	20.92	37.96	51.96	62.39	
Factor weightage	0.36	0.29	0.18	0.18	

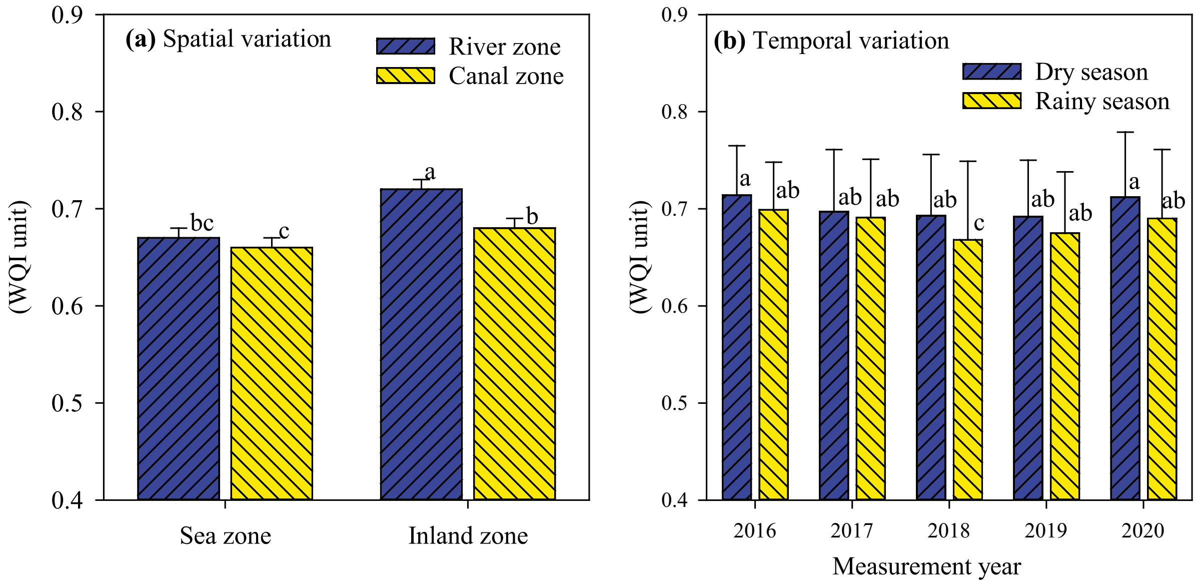

Fig. 2 Spatial and temporal variation of WQI of the study area. Within each panel, bars attached with the same letter are not significantly different from each other according to ANOVA and a Tukey's HSD test ($p < 0.05$). Error bars indicate standard deviation

was the highest in the sea zone and river zone (4776 mg L^{-1}) and was the lowest in the inland zone and river zone (160 mg L^{-1}) (Fig. 4a). Water samples collected from the inland zone exhibited a greater coliform density than those collected from the sea zone (Fig. 4c). The TSS value was the highest in the sea zone and river zone (72.1 mg L^{-1}) and was the lowest in the inland zone and canal zone (40.1 mg L^{-1}) (Fig. 4d). Two water parameters, BOD_5 and oil and grease having a strong relationship with factor 3 were shown in Fig. 3. While the concentration of BOD_5 within the sea zone was much higher in the canal zone (8.3 mg L^{-1}) than in the river zone (7.33 mg L^{-1}) its concentration was similar in the two examined zones located within the inland zone (Fig. 5a). The concentration of oil and grease was not significantly different from the four examined spatial zones (Fig. 5b).

The multivariable regression analysis revealed that the water quality index (WQI) was significantly correlated with all four factors extracted from the PCA/FA analysis, with factors 1, 2, 3, and 4 accounting for 68.3%, 12.8%, 7.0%, and 2.7% of the total variance of the WQI index, respectively (Table 3). All four factors together accounted for 90.8% of the total variance of the WQI.

Discussion

The PCA/FA analysis indicates that there could be four major pollution sources associated with four extracted factors (Tables 1 and 2) that contribute to altering the ten measured quality parameters of the surface water in the current study. Factor 1, having a high loading value with TIN, COD, P, and DO parameters, may suggest that the main pollution source for these parameters could be connected to the activities of agricultural production. Wastewater from agricultural production could contain a large quantity of phosphorus (P) in various forms (Bowes et al., 2015; Butler et al., 1995; Kok et al., 2018). Water from paddy fields may also be characterized by a high concentration of organic matter (Lee et al., 2018), enriching the organic C-based parameters such as COD. Furthermore, runoff water from paddy fields can wash away materials containing N, P, organic matter, and fertilizers (Bertol et al., 2010; Cui et al., 2020; Li et al., 2017), raising the concentration of inorganic nitrogen (TIN), phosphorus (P), and COD in surface water while reducing DO. A high concentration of inorganic nitrogen (TIN) in water may be accompanied by a reduced DO concentration due to the biological oxidation–reduction processes

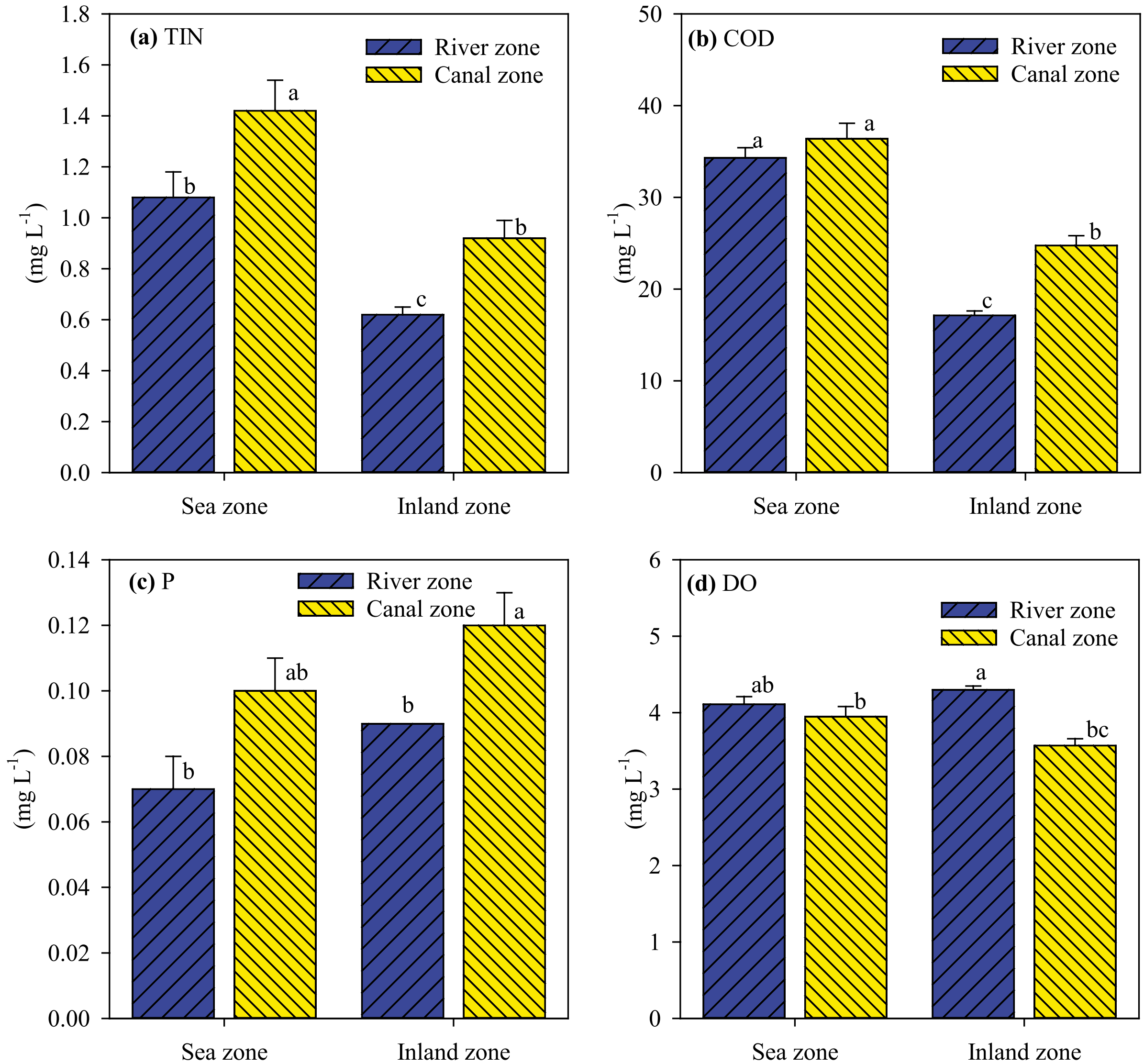

Fig. 3 Water quality parameters for factor 1 as affected by the sea zone and river zone. Within each panel, bars attached with the same letter are not significantly different from each other according to ANOVA and a Tukey's HSD test ($p < 0.05$). Error bars indicate standard deviation. TIN = total inorganic nitrogen

of algae and bacteria (de Almeida Fernandes et al., 2018; Hong et al., 2019; Xia et al., 2018). The pollution source of agricultural production is strongly supported by results from Fig. 3, which showed that the value of TIN, COD, and P was greater in the canal zone than in the river zone. This is because the canal zone is situated inside the study area and is predicted to receive more surface runoff and/or leaching water from the agricultural areas and/or wastewater from aquacultural areas than the river zone. The lower concentration of DO in the canal zone compared to the river zone (Fig. 3d) could be a consequence of a greater concentration of COD and TIN in the canal zone than in the river zone.

Factor 2 has a high association with three parameters, pH, Cl^-, and log(coliform) (Table 2), indicating that saltwater intrusion could be the primary source responsible for these water parameters. Saline intrusion is the main cause of increased Cl^- concentration and EC in surface and groundwater in river basins (Ahmed

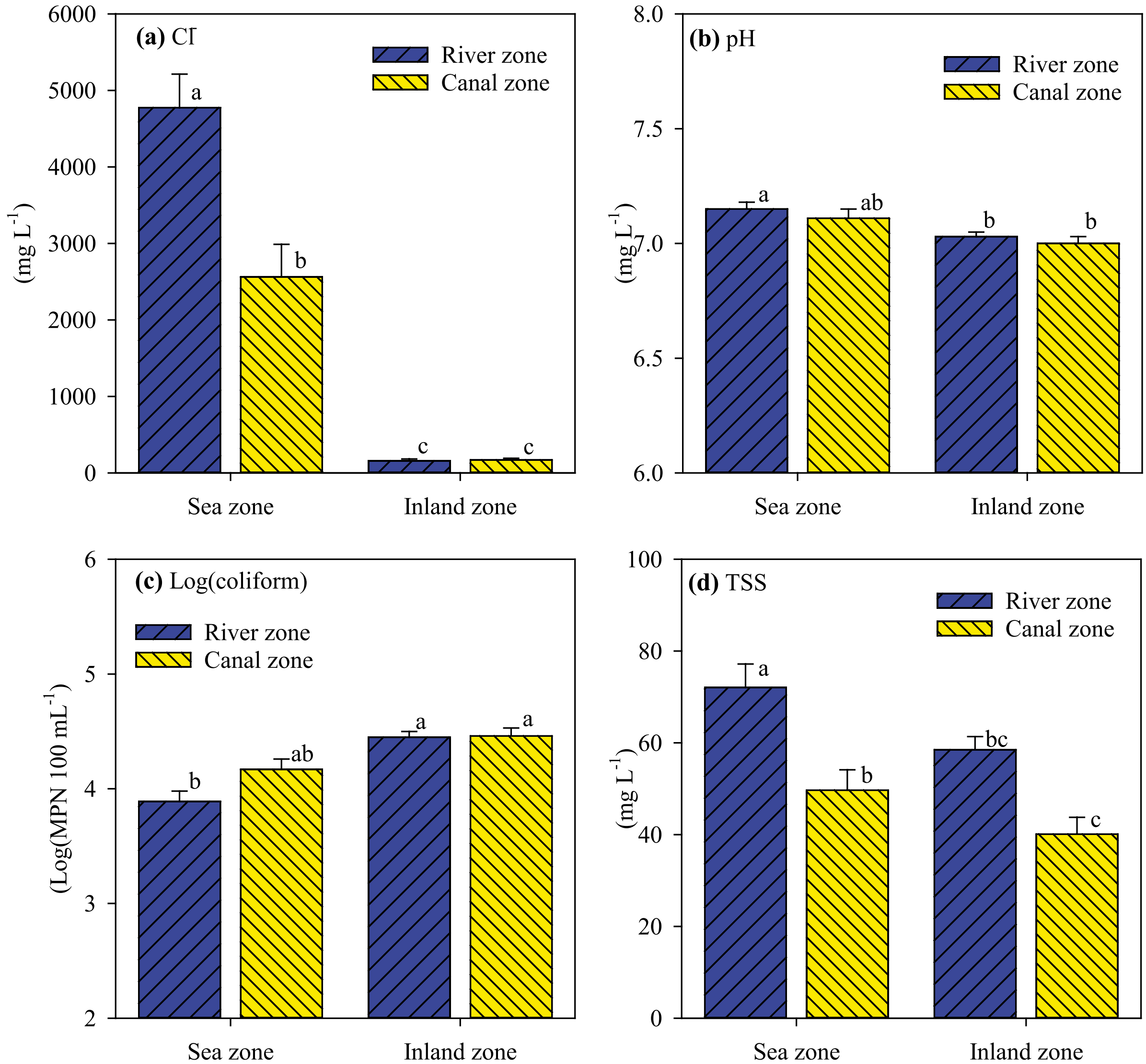

Fig. 4 Water quality parameters for factor 2 (Cl^-, pH, and log(coliform) and factor 4 (TSS) as affected by the sea zone and river zone. Within each panel, bars attached with the same letter are not significantly different from each other according to ANOVA and a Tukey's HSD test ($p < 0.05$). Error bars indicate standard deviation

& Askri, 2016; Alfarrah & Walraevens, 2018; Panjaitan et al., 2018; Nguyen et al., 2021). The seawater intrusion also raises pH value because of the existence of some alkaline elements, such as sodium (Na), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+) in the seawater (Bardi, 2010; Weissman & Tully, 2020). The density and activities of microorganisms such as coliform can be influenced by habitat conditions, which could be unfavorable in the areas affected by seawater intrusion. The seawater intrusion as a pollution source worsening the surface water quality in the study area is further supported by the results from Fig. 4, which showed that the sea zone had a considerably higher value of Cl^-, pH, and a lower coliform density than the inland zone. The value of Cl^- and pH was much greater in the river zone than in the canal zone, especially in the sea zone. This may imply that seawater may enter the study area through the main flow of the two rivers (the Co Chien and Hau Rivers, Fig. 1). These suggest that

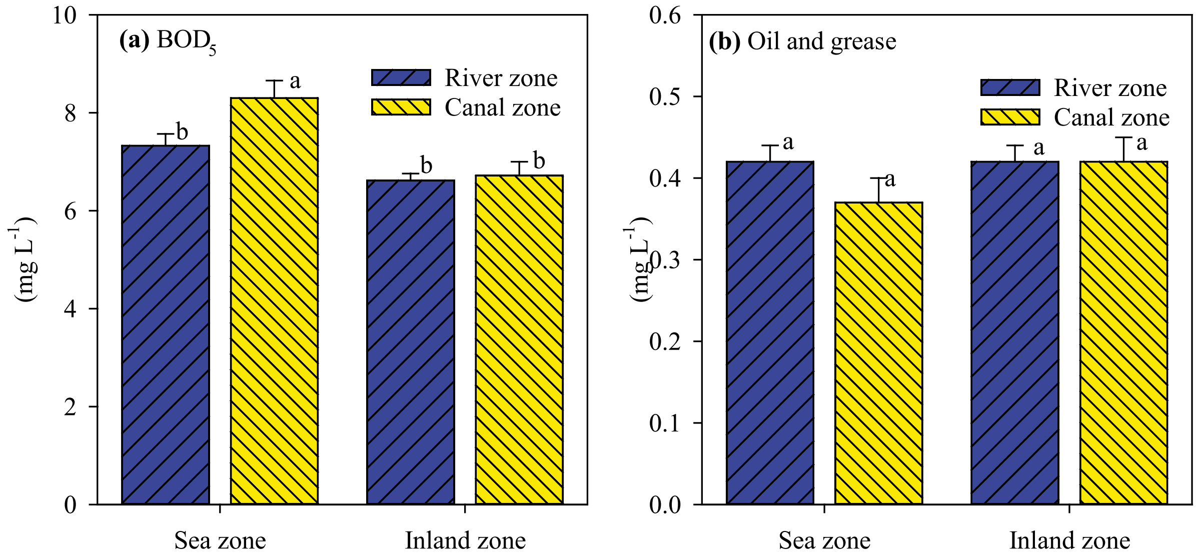

Fig. 5 Water quality parameters for factor 3 as affected by the sea zone and river zone. Within each panel, bars attached with the same letter are not significantly different from each other according to ANOVA and a Tukey's HSD test ($p < 0.05$). Error bars indicate standard deviation

seawater intrusion is typically important in determining the quality of the surface water in the study area.

Two parameters, BOD_5, and total oil and grease having high loading values with factor 3 (Table 2) could be influenced by pollution sources of domestic wastewater and/or industrial production. Domestic wastewater may contain a great quantity of bio-available organic carbon (reflected by BOD_5) and oil and grease derived from bathrooms, kitchens, and toilets. Consequently, water bodies receiving domestic wastewater could be contaminated with high levels of organic carbon, oils, and grease. Several previous studies have attributed the main pollution sources of the C-based parameter of surface water bodies to municipal wastewater discharged from residential areas (Simeonov et al., 2003; Vega et al., 1998).

The concentration of BOD_5 was considerably higher in the canal zone than in the river zone (Fig. 5a), indicating that the pollution source of BOD_5 could be derived from inside the study area, which includes residential areas and the canal zone. The BOD_5 value was also greater in the sea zone than in the inland zone (Fig. 5a), which could be explained by several reasons. The first one could be related to the transport of organic pollutants by river water from the inland zone to the coastal zone, bringing the pollutants to the sea zone. This reason can also be responsible for a similar trend in the spatial variation of COD (its concentration is lower in the inland zone than in the sea zone) as shown in Fig. 3d. The second one could be associated with a process of self-purification (González et al., 2014), which may occur more

Table 3 Percentage of individual latent factors from PCA/FA in explaining the total variance of WQI of the study area. Prob < 0.05 indicates the effect of the considered factor is significant

Latent factor	Sum of Squares	Contribution (%)	Prob > F	Influenced parameters	Pollution sources
Factor 1	1.77	68.3	< 0.0001	TIN, COD, P, DO	Agriculture production
Factor 2	0.33	12.8	< 0.0001	Cl^-, pH, log(coliform)	Seawater intrusion
Factor 3	0.18	7.0	< 0.0001	BOD_5, Oil and grease	Residential activities
Factor 4	0.07	2.7	< 0.0001	TSS	Various sources
Error	0.24	9.2			
Total variance	2.59	100.0			

weakly in the sea zone due to strong salinity than in the inland zone. The concentration of total oil and grease was distributed relatively equally over the four study zones (Fig. 5b). The real causes are still unclear but they could be more likely involved in its physicochemical properties. Oil and grease are surface-floating organic compounds and are relatively stable in the environment. Consequently, they can quickly spread over the surface of water bodies, if there is one contamination point, leading to a statistically similar concentration of the materials over the study area.

TSS is the total suspended solids, which could originate from various sources such as wastewater from residential activities, agricultural production, aquaculture, and freight transport on rivers. Domestic wastewater contains a high quantity of suspended solids and sediments, polluting surface water (Huang et al., 2010). Food residues, manure, and metabolic waste from aquaculture activities can also contaminate surface water with high concentrations of suspended solids (Coldebella et al., 2017; Dauda et al., 2019). In addition, the operation of boats on the river often causes turbidity in the surface water of the water bodies, such as rivers. Therefore, specific pollution sources of TSS are still unclear and may need more study. The TSS concentration was still higher in the sea zone than in the inland zone (Fig. 4d), which could be explained by a process of pollutant transport by river water, similar to those responsible for the spatial variation of BOD_5 and COD.

In brief, three major pollution sources potentially exist to deteriorate the quality of the surface water system in the study area. Agricultural production is the main economic sector of Tra Vinh province, and consequently, agricultural production may be the primary cause of surface water pollution in the province, accounting for around 68% of the total variance of the WQI (Table 3). Because the current study area is based on a coastal area, directly connected to the sea, the second important pollution source degrading the surface water quality of the area could be derived from seawater intrusion, accounting for around 12.8% of the total variance of the WQI. The third one could originate from residential activities and/or industrial production, which may account for a smaller percentage of around 7%. Furthermore, other mixed uncertain pollution sources might contribute to the degradation of the quality of surface water in the current study.

In terms of spatial variation, water samples collected from the river zone had a higher WQI than those collected from the canal zone (Fig. 2a). The reason could be related to the spatial distribution of the two zones, which may receive different pollutant discharge from different pollution sources. The canal zone is situated inside the study area, where agricultural production, such as paddy rice cultivation and fisheries, is carried out annually. Agricultural production is identified as a primary pollution source for the surface water system in the current study (Table 3). On the other hand, the WQI had a general tendency of decreasing from inland to coastal areas (Fig. 2a). The decreasing tendency could be explained by three reasons. The first one could be related to seawater intrusion, which may have a greater influence on the sea zone than the inland zone. The seawater intrusion is also identified as the second most important pollution source deteriorating the quality of surface water in the current study. The second one could be connected to the hydrological flow of fresh water from the upper reaches of the Mekong River through Hau and Co Chien Rivers (Fig. 1), which may carry relatively high-quality fresh water to the study area. Consequently, WQI was much better in the river zone than in the canal zone, as seen in Fig. 2a. The last one could be involved in the transport of pollutants from the upper areas (inland zone) to the lower areas (sea zone), degrading the water quality in the coastal area. The trend of decreasing WQI from the upper zone to the lower zone has also been found in many other rivers such as the Saigon River (Nguyen et al., 2011) and Cau River (Son et al., 2020), Vietnam; Beheshtabad River (Fathi et al., 2018), and Talar River (Darvishi et al., 2016), Iran, and Suceava River (Briciu et al., 2020), Romania.

In terms of temporal variation, the WQI of surface water was greater in the dry season than in the rainy season (Fig. 2b). This disparity might be attributed to runoff and high water levels during the rainy season, which washes contaminants from agricultural land into water bodies (Maprasit et al., 2018; Ofosu et al., 2021; Xiao et al., 2020). Agricultural production was demonstrated to be the primary cause of pollution in the study area, reflected through factor 1 of the PCA/FA (Tables 2 and 3). On the other hand, because the study area is located downstream of the Mekong River, additional pollutants could be carried from upstream and nearby areas to accumulate in the study area during the rainy season. The transport of pollutants from the upstream or adjacent area of a river to downstream areas identified as the main cause of poor water quality has been discovered and studied in many river basins (Babić et al., 2019; Darvishi et al., 2016; Fathi et al., 2018; Nguyen et al., 2011; Son et al., 2020). The change in WQI over the last five years was not significant (Fig. 2a), implying that pollutant discharge from their sources may vary slightly over a period from 2016 to 2020. Nonetheless, with rapid and strong economic and industrial development recently in the study area as well as climate change, the surface water system in the study area may become more degraded due to increased pollutant discharge from agricultural production, particularly industrial activities, as well as seawater intrusion. More research is needed, and subsequent management strategies should be prepared and implemented for a better environment and sustainable development.

Conclusion

Surface water quality in Tra Vinh province tends to decrease from inland to coastal areas, is better in the river zone than in the canal zone, and is higher in the dry season than in the rainy season. Surface water quality can be influenced by 4 primary pollution sources, of which the most important source could be involved in agricultural activities in the area; the second source could be linked to the saline intrusion into rivers and canals; the third source could be derived from residential activities, and the fourth source is a mix of various factors. The transport of pollutants from upstream to downstream of the Mekong River, as well as from inland to coastal areas, and seawater instruction from the coastal areas could be the natural processes primarily responsible for decreasing surface water quality from inland to coastal areas. Erosion and pollutant leaching from the cultivation land into water bodies might be the main causes of the decline in water quality during the rainy season compared to the dry season. In the upcoming time, it is vital to have some feasible methods and policies to manage, regulate, and treat the primary pollution sources for a healthier environment and consequent sustainable development of Tra Vinh province.

Acknowledgements The authors would like to express their sincere gratitude and appreciation to the Department of Natural Resources and Environment of Tra Vinh province, the Industrial University of Ho Chi Minh City (IUH), faculties and students of the Institute of Science, Technology and Environmental Management (IESEM-IUH) for their support, assistance, and contribution to the completion of this work.

Author contribution Thang Viet Le: initiated the study and wrote the draft; Duong Thuy Phuc Nguyen wrote the draft, reviewed, and revised the paper; Binh Thanh Nguyen processed data, established the outline of the current paper, polished, and submitted the paper. All authors reviewed the manuscript.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Competing interests The authors declare no competing interests.

References

Ahmed, A., & Askri, B. (2016). Seawater intrusion impacts on the water quality of the groundwater on the Northwest Coast of Oman. *Water Environment Research, 88*, 732–740.

Akhtar, M., & Memon, M. (2009). Biomass and nutrient uptake by rice and wheat: A three-way interaction of potassium, ammonium and soil type. *Pakistan Journal of Botany*, *41*.

Alfarrah, N., & Walraevens, K. (2018). Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-Arid Regions. *Water, 10*, 143.

Babić, G., Milovan, V., Voza, D., Takić, L., & Mladenović-Ranisavljević, I. (2019). Assessing surface water quality in the Serbian part of the Tisa River Basin. *Polish Journal of Environmental Studies*.

Banda, T., & Kumarasamy, M. (2020). Application of multivariate statistical analysis in the development of a surrogate water quality index (WQI) for south African watersheds. *Water, 12*, 1584.

Bardi, U. (2010). Extracting minerals from seawater: An energy analysis. *Sustainability, 2*(4), 980–992.

Behmel, S., Damour, M., Ludwig, R., & Rodriguez, M. J. (2016). Water quality monitoring strategies — A review and future perspectives. *Science of the Total Environment, 571*, 1312–1329.

Bertol, O. J., Rizzi, N. E., Favaretto, N., & Lana, M. D. C. (2010). Phosphorus loss by surface runoff in no-till system under mineral and organic fertilization. *Scientia Agricola, 67*, 71–77.

Bowes, M. J., Jarvie, H. P., Halliday, S. J., Skeffington, R. A., Wade, A. J., Loewenthal, M., Gozzard, E., Newman, J. R., & Palmer-Felgate, E. J. (2015). Characterising phosphorus and nitrate inputs to a rural river using high-frequency concentration-flow relationships. *Scien Total Environment, 511*, 608–620.

Briciu, A.-E., Graur, A., & Dinu, O. (2020). Water quality index of Suceava River in Suceava City Metropolitan Area. *Water, 12*, 2111.

Butler, D., Friedler, E., & Gatt, K. (1995). Characterising the quantity and quality of domestic wastewater inflows. *Water Science and Technology, 31*(7), 13–24.

Coldebella, A., Gentelini, A., Piana, P., Coldebella, P., Boscolo, W., & Feiden, A. (2017). Effluents from fish farming ponds: A view from the perspective of Its main components. *Sustainability, 10*, 3.

Cui, N., Cai, M., Zhang, X., Abdelhafez, A. A., Zhou, L., Sun, H., Chen, G., Zou, G., & Zhou, S. (2020). Runoff loss of nitrogen and phosphorus from a rice paddy field in the east of China: Effects of long-term chemical N fertilizer and organic manure applications. *Global Ecology and Conservation, 22*, e01011.

Darvishi, G., Kootenaei, F., Ramezani, M., Lotfi, E., & Asgharnia, H. (2016). Comparative investigation of river water quality by OWQI, NSFWQI and Wilcox Indexes (Case study: The Talar River - Iran). *Archives of Environmental Protection*, *42*.

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture and Fisheries, 4*(3), 81–88.

de Almeida Fernandes, L., Pereira, A. D., Leal, C. D., Davenport, R., Werner, D., Filho, C. R. M., Bressani-Ribeiro, T., de Lemos Chernicharo, C. A., & de Araújo, J. C. (2018). Effect of temperature on microbial diversity and nitrogen removal performance of an anammox reactor treating anaerobically pretreated municipal wastewater. *Bioresource Technology, 258*, 208–219.

DonRe. (2020). Report on environmental status of Tra Vinh province in the period 2016–2020, Department of Natural Resources and Environment of Tra Vinh province.

Eqani, S. A., Malik, R. N., & Mohammad, A. (2011). The level and distribution of selected organochlorine pesticides in sediments from River Chenab, Pakistan. *Environmental Geochemistry and Health, 33*(1), 33–47.

Fathi, E., Zamani-Ahmadmahmoodi, R., & Zare Bidaki, R. (2018). *Water quality evaluation using water quality index and multivariate methods, Beheshtabad River* (p. 8). Applied Water Science.

Giri, A., Bharti, V. K., Kalia, S., Arora, A., Balaje, S. S., & Chaurasia, O. P. (2020). A review on water quality and dairy cattle health: A special emphasis on high-altitude region. *Applied Water Science, 10*(3), 79.

González, S. O., Almeida, C. A., Calderón, M., Mallea, M. A., & González, P. (2014). Assessment of the water self-purification capacity on a river affected by organic pollution: Application of chemometrics in spatial and temporal variations. *Environmental Science and Pollution Research, 21*(18), 10583–10593.

Hajrasuliha, S., Cassel, D. K., & Rezainejad, Y. (1991). Estimation of chloride ion concentration in saline soils from measurement of electrical conductivity of saturated soil extracts. *Geoderma, 49*(1), 117–127.

Hong, P., Wu, X., Shu, Y., Wang, C., Tian, C., Gong, S., Cai, P., Donde, O. O., & Xiao, B. (2019). Denitrification characterization of dissolved oxygen microprofiles in lake surface sediment through analyzing abundance, expression, community composition and enzymatic activities of denitrifier functional genes. *AMB Express, 9*(1), 129–129.

Huang, M.-H., Li, Y.-M., & Gu, G.-W. (2010). Chemical composition of organic matters in domestic wastewater. *Desalination, 262*(1), 36–42.

Ibrahim, T., Othman, F., Mahmood, N., & Abunama, T. (2021). Seasonal effects on spatial variations of surface water quality in a tropical river receiving anthropogenic influences. *Sains Malaysiana, 50*, 571–593.

IPCC. (2019). Climate Change and Land, IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Kok, D.-J.D., Pande, S., van Lier, J. B., Ortigara, A. R. C., Savenije, H., & Uhlenbrook, S. (2018). Global phosphorus recovery from wastewater for agricultural reuse. *Hydrology and Earth System Sciences, 22*, 5781–5799.

Lee, T.-G., Lee, C.-G., Hong, S.-G., Kim, J.-H., & Park, S.-J. (2018). Water and soil properties in organic and conventional paddies throughout the rice cultivation cycle in South Korea. *Environmental Engineering Research*, 24.

Li, S., Li, J., Li, G., Li, Y., Yuan, J., & Li, D. (2017). Effect of different organic fertilizers application on soil organic matter properties. *Compost Science & Utilization, 25*(sup1), S31–S36.

Maprasit, S., Darnsawasdi, R., Rangpan, V., & Suksaroj, C. (2018). Spatial variations of surface water quality and pollution sources in Khlong U-Tapao river basin. *International Journal of GEOMATE, 14*, 98–103.

Mateo-Sagasta, J., Marjani, S., & Turral, H. (2018). More people, more food, worse water?: A global review of water pollution from agriculture. The Food and Agriculture Organization of the United Nations Rome and the International Water Management Institute on behalf of the Water Land and Ecosystems research program of the CGIAR Colombo.

Monre. (2015). National technical regulation on surface water quality QCVN 08-MT:2015/BTNMT, Ministry of Natural Resources and Environment. Ha Noi.

Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLoS ONE, 9*(8), e105981–e105981.

Nguyen, B., Le, L., Le Hung, A., & Thai, V. (2021). 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. *Environmental Monitoring and Assessment*, *193*.

Nguyen, T. N., Ha, N., & Sthiannopkao, S. (2011). Risk assessment of the Sai Gon river water quality for safety water supply to Ho Chi Minh city. *Journal of Science and Technology*.

Nguyen, T. T. N., Némery, J., Gratiot, N., Strady, E., Tran, V. Q., Nguyen, A. T., Aimé, J., & Peyne, A. (2019). Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon – Dongnai (southern Vietnam). *Science of the Total Environment, 653*, 370–383.

Ofosu, A., Adjei, K., & Odai, S. (2021). Assessment of the quality of the Densu river using multicriterial analysis and water quality index. *Applied Water Science*, *11*.

Okello, C., Tomasello, B., Greggio, N., Nina, W., & Antonellini, M. (2015). Impact of population growth and climate change on the freshwater resources of Lamu Island, Kenya. *Water, 7*, 1264–1290.

Oketola, A., Okekunle, M., & Osibanjo, O. (2013). Water quality assessment of River Ogun using multivariate statistical techniques. *Journal of Environmental Protection, 4*, 466–479.

Panjaitan, D., Tarigan, J., Rauf, A., & Nababan, E. S. (2018). Determining sea water intrusion in shallow aquifer using chloride bicarbonate ratio. *IOP Conference Series: Earth and Environmental Science* 205, 012029.

Pham, H., Rahman, M. M., Nguyen, N. C., Vo, P., Van, T., & Ngo, H. (2017). Assessment of surface water quality using the water quality index and multivariate statistical techniques—A case study: The upper part of Dong Nai river basin, Vietnam. *Journal of Water Sustainability, 7*, 225–245.

Phung, D., Huang, C., Rutherford, S., Dwirahmadi, F., Chu, C., Wang, X., Nguyen, M., Nguyen, N., Do, C., Nguyen, T., & Dihn, T. A. D. (2015). Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: A study in Can Tho City, a Mekong Delta area, Vietnam. *Environmental Monitoring and Assessment, 187*, 4474.

Putri, M., Lou, C.-H., Syai'in, M., Ou, S.-H., & Wang, Y.-C. (2018). Long-term river water quality trends and pollution source apportionment in Taiwan. *Water, 10*, 1394.

Simeonov, V., Stratis, J. A., Samara, C., Zachariadis, G., Voutsa, D., Anthemidis, A., Sofoniou, M., & Kouimtzis, T. (2003). Assessment of the surface water quality in Northern Greece. *Water Research, 37*(17), 4119–4124.

Son, C. T., Giang, N. T. H., Thao, T. P., Nui, N. H., Lam, N. T., & Cong, V. H. (2020). Assessment of Cau River water quality assessment using a combination of water quality and pollution indices. *Journal of Water Supply: Research and Technology-Aqua, 69*(2), 160–172.

Thanh Giao, N., Kim Anh, P., & Thi Hong Nhien, H. (2021). Spatiotemporal analysis of surface water quality in Dong Thap province, Vietnam using water quality index and statistical approaches. *Water, 13*(3), 336.

Tirkey, P., Bhattacharya, T., & Chakraborty, S. (2013). Water quality indices- important tools for water quality assessment: a review. *International Journal of Advances in Chemistry (IJAC)*, *1*.

Vega, M., Pardo, R., Barrado, E., & Debán, L. (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Research, 32*(12), 3581–3592.

Weissman, D. S., & Tully, K. L. (2020). Saltwater intrusion affects nutrient concentrations in soil porewater and surface waters of coastal habitats. *Ecosphere, 11*(2), e03041.

Xia, X., Zhang, S., Li, S., Zhang, L., Wang, G., Zhang, L., Wang, J., & Li, Z. (2018). The cycle of nitrogen in river systems: sources, transformation, and flux. *Environmental Science: Processes & Impacts*, *20*.

Xiao, L., Zhang, Q., Niu, C., & Wang, H. (2020). Spatiotemporal patterns in river water quality and pollution source apportionment in the arid Beichuan River basin of northwestern China using positive matrix factorization receptor modeling techniques. *International Journal of Environmental Research and Public Health, 17*(14), 5015.

Yang, S., Liang, M., Qin, Z., Qian, Y., Li, M., & Cao, Y. (2021). A novel assessment considering spatial and temporal variations of water quality to identify pollution sources in urban rivers. *Scientific Reports, 11*(1), 8714.