Hydrological Sciences Journal

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/thsj20

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To cite this article: Binh Thanh Nguyen, Vinh Ngoc Nguyen, Tong Xuan Nguyen, Thanh Dang My & Anh Hoang Le (16 Sep 2024): Pollution-source fractionation and quantification-based assessment of surface water quality in Saigon River, Vietnam: implications for sustainable management strategies, Hydrological Sciences Journal, DOI: 10.1080/02626667.2024.2393794

To link to this article: https://doi.org/10.1080/02626667.2024.2393794

HYDROLOGICAL SCIENCES JOURNAL
https://doi.org/10.1080/02626667.2024.2393794

Pollution-source fractionation and quantification-based assessment of surface water quality in Saigon River, Vietnam: implications for sustainable management strategies

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ABSTRACT
The current study fractionated pollution sources and investigated the impacts of seasonal and tidal variations on Saigon River's surface water quality. Ninety-six water samples were collected across dry and rainy seasons, covering ebb and flood tides, and analysed for 19 parameters. During the dry season, ebb tide showed higher levels of electrical conductivity, sulfate, chloride, sodium, and potassium. During the rainy season, ebb tide exhibited greater concentrations of ammonium, total nitrogen, and phosphorus. The water quality index was significantly lower during the dry season's ebb tide compared to the flood tide but remained similar in both tidal phases during the rainy season. Four primary pollution sources were quantified, with seawater intrusion and agricultural activities contributing 62.68% and 28.54%, respectively, to water quality degradation. Briefly, the river's surface water quality was inferior during the dry season compared to the rainy season, primarily due to seawater intrusion and agricultural activities, requiring remediation.

ARTICLE HISTORY
Received 31 October 2023
Accepted 24 July 2024

EDITOR
R. Singh

ASSOCIATE EDITOR
M. Hutchins

KEYWORDS
agricultural pollution source; residential area; river water; seawater intrusion; seasonal variation; tidal phase

1 Introduction

Monitoring and maintaining river surface water quality is crucial for protecting human health, supporting agricultural activities, ensuring a reliable water supply, and protecting the environment for future generations (Mishra *et al.* 2021, Makanda *et al.* 2022). However, surface water in rivers is susceptible to degradation due to various activities such as agricultural production, residential development, boat and cargo ship operations, and aquaculture (Khan and Wen 2021, Hong and Giao 2022, Wehrheim *et al.* 2023). In addition, rivers in coastal areas may suffer from seawater intrusion, leading to salt contamination (Mohammed and Scholz 2017, Prusty and Farooq 2020, Le *et al.* 2023a). Although numerous studies have been conducted to assess various factors influencing the quality of rivers (Anh *et al.* 2023, Uddin *et al.* 2024), an insufficient number of them have focused on fractionating and quantifying individual pollution sources. Furthermore, the interaction between anthropogenic pollution sources (such as agricultural and residential activities) and natural factors (such as seasonal variation and tidal regime) that possibly determine the river quality is only limitedly discussed in the literature and should be clearly quantified. Accurate identification, fractionation, and quantification of these factors and pollution sources are important for developing and implementing effective management strategies.

Surface water in rivers can be influenced by diverse pollution sources such as agriculture, domestic wastewater from residential areas, saltwater intrusion, and stormwater runoff (Khan *et al.* 2015, Giao and Ly 2023). During the rainy season, on the one hand, more pollutants may be transported to rivers, degrading their water quality; on the other hand, increased dilution and reduced residence time can improve the water quality of rivers (Yang *et al.* 2021). Conversely, the dry season, with low rainfall, results in low water flow and volume, raising the pollutant concentrations in rivers (Mosley 2015). These findings led to our first hypothesis, presented at the end of this section.

Different pollution sources exhibit distinct characteristics, which set them apart from one another. The pollution sources derived from agricultural areas may deteriorate river water quality with high levels of nitrogen, phosphorus, and some chemical compounds derived from applied chemical fertilizers and pesticides (Rey-Romero *et al.* 2022, Xu *et al.* 2022). Seasonal variation in river water parameters was also reported by Khan *et al.* (2017), dependent on pollution sources. Intensive agricultural production of various crops, commonly occurring during the rainy season, may release a great amount of agriculture-originating pollutants into the surrounding water system. These findings resulted in our second hypothesis presented at the end of this section.

Furthermore, rivers in coastal areas can be influenced by seawater intrusion in addition to seasonal variation (Tang *et al.* 2020). Although seawater intrusion may occur to a certain extent during the rainy season, high rainfall during this season leading to greater freshwater recharge, enhanced river flow, and dilution effects typically helps mitigate the

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/02626667.2024.2393794

intrusion (Garcés-Vargas *et al.* 2020, Stein *et al.* 2023). During the dry season, with low rainfall and freshwater recharge, seawater intrusion becomes more pronounced (Descroix *et al.* 2020). The dynamics and water composition of coastal rivers are also influenced by tidal cycles, with flood tides introducing seawater into rivers and ebb tides extracting it from rivers. These suggest a significant interaction between seasons and the tidal phases on river water quality, which is limitedly discussed in the literature. Therefore, our third hypothesis was formulated and is presented at the end of this section.

Another important source influencing river water quality is residential areas, which discharge domestic wastewater into surrounding water systems annually (Joshua *et al.* 2017). Domestic wastewater from these areas is typically rich in organic carbon substances and nutrients (Khan *et al.* 2020, Koul *et al.* 2022). Since residential areas are often situated near or alongside rivers, domestic wastewater may be directly discharged into waterways connected to rivers. In this regard, ebb tides may serve as a significant mechanism for transporting wastewater from residential areas to rivers. Therefore, our fourth research hypothesis was formed and shown at the end of this section.

Therefore, the current study was conducted to assess surface water quality, fractionate and quantify pollution sources, and investigate the combined effects of seasonal variation and tidal phases on the Saigon River. The river, situated in coastal areas with semidiurnal tidal cycles, originates from an agriculture-based basin and passes through the rapidly growing Ho Chi Minh City. Consequently, the surface water of the river could be influenced by multiple pollution sources, as well as seasonal variations and ocean tides. The current study tests four research hypotheses:

Hypothesis 1: The overall water quality in rivers is generally lower during the dry season than during the rainy season.

Hypothesis 2: Componential water quality reflecting agricultural pollution sources is lower during the rainy season than during the dry season.

Hypothesis 3: During the dry season, flood tides significantly lower the componential water quality, reflecting seawater intrusion, while during the rainy season, the impact of flood tides becomes non-significant compared to the influence of ebb tides.

Hypothesis 4: Ebb tides have a more pronounced effect on degrading the componential water quality, reflecting residential pollution sources compared to flood tides.

2 Materials and methods

2.1 The study area

The Saigon River originates in Binh Phuoc province and passes through Tay Ninh and Binh Duong provinces before reaching Ho Chi Minh City, where it joins the Dong Nai River (Fig. 1). With a total basin area of 4717 km^2 and a length of around 256 km (Nguyen *et al.* 2020), the river flows through Ho Chi Minh City for about 80 km, which is where the current study was conducted. The river basin exhibits distinct land use patterns, with agricultural activities such as paddy rice cultivation and rubber tree plantations being prevalent. Urban settlements become increasingly prominent in the lower reaches of the river as it flows through Ho Chi Minh City.

The Saigon River is situated in a monsoon region with two distinct seasons: the rainy season (May to October) and the dry season (December to April) (Nguyen *et al.* 2019a) (see Supplementary material, Fig. S1). Ho Chi Minh City receives an annual rainfall of approximately 1934 mm, with 90% of the rainfall occurring during the rainy season. Consequently, the Saigon River experiences about 90% of its total water discharge during the rainy season, while the dry season is characterized by frequent droughts and low water flows. The river's hydrological regime is influenced by semi-diurnal tidal cycles, flows from the upper basin, and tributaries derived from Ho Chi Minh City, as well as seasonal variations and tidal phases, all of which shape the river's water dynamics.

2.2 Experimental factors and set-up

The current study was conducted to capture the effects of seasonal variation and tidal phase, as well as to fractionate and quantify primary pollution sources contributing to the degradation of the Saigon River. The study involved multiple implementation stages (see Supplementary material, Fig. S2). Seasonal variation (rainy and dry seasons) and tidal phases (ebb tide and flood tide) were considered the two experimental factors. Surface water samples were collected in four separate campaigns, each representing a specific combination of seasonal and tidal conditions. One campaign was conducted during the dry season and ebb tide, another during the dry season and flood tide, one during the rainy season and ebb tide, and the final campaign during the rainy season and flood tide.

2.3 Description of sampling sites, sampling campaign, and chemical analysis

For each sampling campaign, water samples were collected from 13 pre-selected sites from the 50 cm surface layer of water (Fig. 1). At the two sites located at the two ends of the study reach of the river, one water sample per site was taken to examine the input and output water quality for comparison. At the other 11 sites, located in the middle of the river, two water samples were taken at each site that was pre-selected at the confluence of the river with its tributaries. Because these middle sites were located at the confluence, potentially leading to great variation in water quality, collecting two water samples at one site was done to increase the number of replicates of water samples, thus minimizing random variation in water quality data (more information on water sampling is given in Supplementary material, Text S1). Consequently, a total of 96 water samples (4 campaigns × 11 sites × 2 samples/

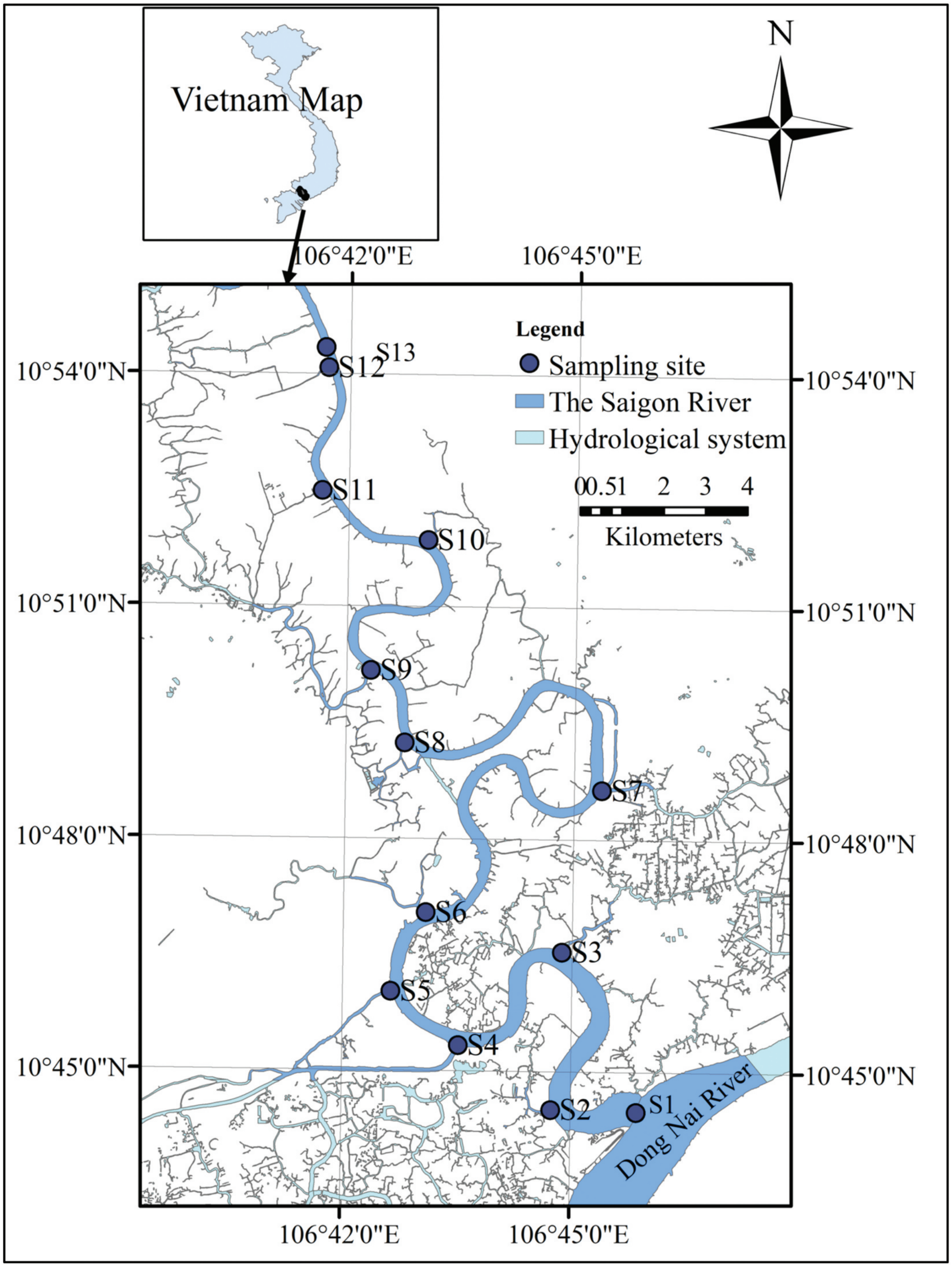

Figure 1. Sampling sites and map of the Saigon River in Ho Chi Minh City, Vietnam.

site + 4 campaigns × 2 sites × 1 sample/site) were collected for the current study. A powerboat was used to collect water samples, covering a distance of 43 km from the river's mouth to the other end of the study reach during each campaign. The water samples were obtained using a Van Dorn water sampler, following the procedure described by Nguyen *et al.* (2021).

After collection, the water samples were rapidly transferred to a laboratory for chemical analysis. Water parameters such as temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were measured in situ using a pH meter (Thermo Scientific™ Orion™ 3-Star Benchtop pH Meter), an EC meter (Oaklon conductivity, TDS, °C Meter, Con 11 series), and a portable DO meter (Oxygen 3210 portable dissolved oxygen Meter), respectively (Table 1). The in-laboratory analysis included NH_4^+-N, NO_3^--N, total N, total suspended solids (TSS), total P, five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), coliform bacteria, Na, K, Ca, Mg, Cl^-, and sulfate (SO_4^{2-}) (Table 1). The first eight parameters were determined using the national standard procedure (MONRE 2015) and following Nguyen

Table 1. The levels of 19 water parameters in two seasons and tidal phases.

		Rainy season				Dry season				
		Ebb tide		Flood tide		Ebb tide		Flood tide		
Water parameter	Unit	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Interaction
Temperature	°C	30.02^{c}	0.18	30.73^{b}	0.08	30.25^{c}	0.08	31.81^{a}	0.10	*
pH	None	7.14^{a}	0.06	7.26^{a}	0.02	6.44^{c}	0.03	6.88^{b}	0.03	*
DO	mg L^{-1}	2.36^{b}	0.19	2.79^{ab}	0.15	3.32^{a}	0.15	3.31^{a}	0.08	NS
EC	µS cm^{-1}	241.7^{c}	19.93	535.60^{c}	125.88	4649.0^{a}	523.51	2625.8^{b}	230.34	*
Turbidity	NTU	50.79^{a}	2.43	31.72^{b}	2.10	21.08^{c}	1.60	19.60^{c}	0.99	*
NH_4^+-N	mg L^{-1}	1.97^{a}	0.16	1.64^{ab}	0.20	1.23^{b}	0.25	0.46^{c}	0.11	NS
NO_3^--N	mg L^{-1}	0.27^{c}	0.02	0.24^{c}	0.03	0.55^{b}	0.03	0.66^{a}	0.02	*
Total N	mg L^{-1}	3.15^{a}	0.18	2.73^{ab}	0.25	2.60^{ab}	0.24	2.14^{c}	0.19	NS
BOD_5	mg L^{-1}	10.54^{a}	1.04	8.25^{b}	0.51	10.33^{a}	0.46	8.17^{b}	0.45	NS
COD	mg L^{-1}	23.17^{a}	2.56	16.67^{b}	1.00	18.96^{ab}	0.64	15.38^{b}	0.91	NS
SO_4^{2-}	mg L^{-1}	51.71^{c}	2.50	25.83^{d}	2.95	101.13^{a}	9.82	77.25^{b}	3.42	NS
Total P	mg L^{-1}	0.38^{a}	0.02	0.23^{b}	0.03	0.14^{bc}	0.03	0.07^{c}	0.01	NS
Cl^-	mg L^{-1}	322.8^{b}	24.59	487.41^{b}	64.24	1337.6^{a}	166.26	584.21^{b}	45.97	*
TSS	mg L^{-1}	45.3^{ab}	3.23	27.03^{c}	4.29	57.38^{a}	2.77	41.75^{b}	2.48	NS
Coliform	**	0.89^{b}	0.01	0.85^{b}	0.02	4.40^{a}	0.26	4.77^{a}	0.26	NS
Na	mg L^{-1}	34.24^{b}	4.67	97.96^{b}	19.33	215.86^{a}	29.36	82.97^{b}	8.18	*
K	mg L^{-1}	6.05^{c}	0.81	4.92^{c}	0.74	84.08^{a}	10.20	58.62^{b}	3.62	*
Ca	mg L^{-1}	1.73^{c}	0.17	1.16^{c}	0.09	6.04^{a}	0.42	4.03^{b}	0.14	*
Mg	mg L^{-1}	2.14^{c}	0.18	3.37^{c}	0.64	61.62^{a}	7.82	34.54^{b}	2.73	*

Within a row, data (mean column) followed by the same letter are not significantly different from each other. * and NS indicate the interaction effect between tidal phases and seasons is statistically significant and non-significant, respectively, at P ≤ 0.05. ** is log (MPN 100 mL^{-1}). SD is the standard deviation

et al. (2019b). Na, K, Ca, and Mg were measured using an inductively coupled plasma-optical emission spectrometry (ICP-OES) after filtering and acidifying the water samples (Giri and Singh 2013). The concentrations of Cl^- and SO_4^{2-} were determined using a titration method (Hajrasuliha *et al.* 1991) and a turbidimetric method (Rice *et al.* 2017), respectively.

2.4 Statistical analyses

The principal component analysis/factor analysis (PCA/FA) was carried out on the entire dataset to determine and quantify the pollution sources contributing to the degradation of surface water quality, following the method outlined in a previous study (Le *et al.* 2023a). Prior to conducting PCA/FA, the suitability of the dataset for PCA/FA was assessed using the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity (Banda and Kumarasamy 2020). The overall water quality index (WQI) was computed using Equation (1) (Le *et al.* 2023b):

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

where i is the water parameter; n represents the total number of water parameters (n = 19); w_i is the weightage

Table 2. Loading values of 19 water quality parameters from principal component analysis/factor analysis with four varimax factors.

	Varimax factors				
Water parameter	Factor 1	Factor 2	Factor 3	Factor 4	Parameter weightage (w_i)
Mg	**0.95**	−0.16	0.18	0.04	0.092
EC	**0.95**	−0.15	0.19	0.02	0.092
Cl^-	**0.95**	−0.19	−0.12	0.03	0.092
K	**0.91**	−0.12	0.29	0.06	0.092
Ca	**0.91**	−0.03	0.30	0.13	0.092
SO_4^{2-}	**0.87**	−0.15	0.13	0.15	0.092
Na	**0.86**	−0.23	−0.16	0.00	0.092
pH	**−0.75**	−0.09	−0.36	−0.24	0.092
Total N	−0.08	**0.94**	0.00	0.06	0.039
NH_4^+-N	−0.14	**0.92**	−0.23	0.09	0.039
Total P	−0.22	**0.70**	−0.46	0.10	0.039
DO	0.34	**−0.62**	0.20	−0.32	0.039
Turbidity	−0.25	0.05	**−0.71**	0.38	0.016
Coliform	0.56	−0.20	**0.70**	0.01	0.016
NO_3^--N	0.41	−0.24	**0.68**	0.19	0.016
Temperature	−0.16	−0.25	**0.63**	−0.14	0.016
BOD_5	0.10	0.22	−0.09	**0.90**	0.016
COD	0.00	0.16	−0.22	**0.89**	0.016
TSS	0.34	−0.02	0.09	**0.64**	0.016
Eigenvalue	8.73	3.67	1.55	1.50	
% total variance	45.93	19.32	8.17	7.87	
Cumulative percentage variance	45.93	65.25	73.42	81.29	
Factor weightage	0.56	0.24	0.10	0.10	

Bold numbers are those greater than 0.5.

of the i^th^ parameter, and s_i is the score of the i^th^ parameter. w_i was determined using PCA/FA results (Table 2) and s_i corresponded to the standardized value of individual parameters (more information on the methods is shown in Supplementary material, Text S2). Furthermore, the overall WQI was fractionated into componential WQIs reflecting the pollution sources identified through PCA/FA. The componential WQIs were computed based on varimax factors extracted from PCA/FA (Table 2), using Equation (2):

$$\text{Componential WQI} = \sum\nolimits_{j,i=1}^{z} w_i s_i \qquad (2)$$

where z is the total number of water parameters having high loading value with varimax factor j derived from PCA/FA (four varimax factors were identified and are presented in Table 2; j = 1 ... 4). The terms i, w_i and s_i are the same as those in Equation (1).

The relationship between overall WQI and componential WQIs with the distance from the river's mouth was explored using scatter plots. The data from the current study, including overall WQI and componential WQIs, were subjected to a two-way analysis of variance (ANOVA) of a two-factor completely randomized design with varying replicates. Two experimental factors were seasonal variation and tidal phase. The two-way ANOVA model used was

$$y_{fgh} = \mu + \beta_f + \propto_g + \beta\alpha_{fg} + \varepsilon_{fgh}, \qquad (3)$$

where y_{fgh} is the response of individual combinations of the two experimental factors (seasonal variation and tidal phase); μ is the overall mean; β_f represents the effect of the f^th^ season; $\propto_g$ represents the effect of the g^th^ tide; $\beta\alpha_{fg}$ representes the interaction between seasons and tides; and ε_{fgh} is the random error with a mean zero and normal distribution (Akhtar and Memon 2009). A multivariable regression analysis was conducted to determine the proportional contribution of four componential WQIs (pollution sources) in explaining the total variance of the overall WQI. Pearson correlation coefficients among the 19 water parameters were also computed.

3 Results

3.1 Physiochemical characteristics of the river surface water

The surface water samples collected during the dry season and ebb tide exhibited the highest levels of DO (3.32 mg L^{-1}), EC (4649.0 μS cm^{-1}), BOD_5 (10.33 mg L^{-1}), SO_4^{2-} (101.13 (mg L^{-1}), Cl^- (1337.6 mg L^{-1}), TSS (57.38 mgL^{-1}), coliform (4.40 log(MPN 100 mL^{-1})), Na (215.86 mg L^{-1}), K (84.08 mg L^{-1}), Ca (6.04 mg L^{-1}), and Mg (61.61 mg L^{-1}) (Table 1). Meanwhile, those collected during the dry season and flood tide had the highest levels of temperature (31.81°C), DO (3.33 mg L^{-1}), NO_3^--N (0.66 mg L^{-1}), and coliform (4.77 log (MPN 100 mL^{-1})). Statistically significant differences were observed in all 19 measured water parameters among the four combinations of season and tidal phase: rainy season and ebb tide, rainy season and flood tide, dry season and ebb tide, and dry season and flood tide. Water samples collected during the dry season and ebb tide had the highest number of parameters having the highest levels compared to the other combinations.

3.2 Principal component analysis/factor analysis

Table 2 shows that the 19 water parameters were grouped into four primary varimax factors, based on PCA/FA. Factor 1 had a strong relationship with eight parameters: Mg, EC, Cl^-, K, Ca, SO_4^{2-}, Na, and pH, with absolute correlation coefficients greater than 0.7. Factor 2 showed a strong loading value with four parameters, which were total N, NH_4^+-N, total P, and DO. Factor 3 exhibited a notable connection with four parameters: turbidity, coliform, NO_3^--N, and temperature. Factor 4 was well correlated with BOD_5,

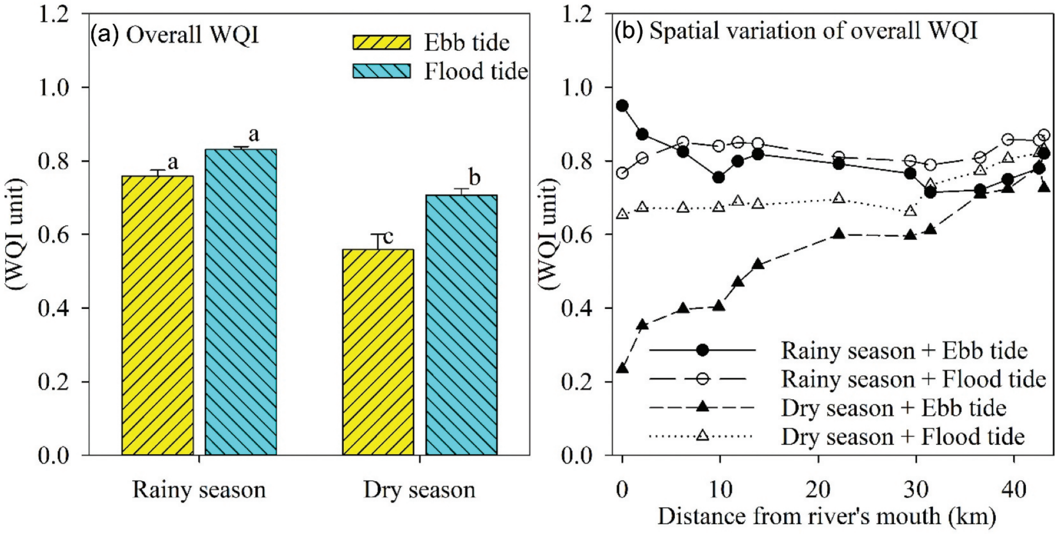

Figure 2. Overall water quality index (WQI) in two seasons and two tidal phases (a) and spatial variation of overall WQI over the distance from the river's mouth (b). For panel a, the bars with the same letter are not significantly different from the other. Error bars indicate the standard deviation. The interaction effect between tidal phases and seasons is statistically significant at P ≤ 0.05.

COD, and TSS. Collectively, the four factors explained 81.29% of the total variance of the whole dataset, with factor 1 explaining the largest proportion, of 45.93%. The inter-correlation among the 19 water parameters was examined and is shown in Supplementary material, Table S1.

3.3 Surface water quality

The overall WQI was statistically significantly affected by the interaction between seasonal variations and tidal phases (Fig. 2(a)). During the rainy season, water samples collected during both tidal phases (ebb and flood tides) had similar overall WQI. In contrast, during the dry season, water samples collected during flood tides exhibited a statistically greater overall WQI than those collected during ebb tides. The overall WQI also varied greatly with the distance from the river's mouth (Fig. 2(b)). Within approximately 30 km from the river's mouth, substantial differences in overall WQI were observed among the four combinations of seasonal variations and tidal phases. Beyond 30 km to 43 km, the overall WQI changed slightly. Starting from the river's mouth, the overall WQI greatly increased from 0.23 to 0.73 (WQI units) during the dry season and ebb tide, while it slightly improved from 0.65 to 0.86 during the dry season and flood tide. During the rainy season, the overall WQI remained relatively consistent across the examined reaches of the Sai Gon River, regardless of tidal phases.

The VF1-WQI (componential WQI based on varimax factor 1) of water samples collected during the rainy season showed no statistically significant difference between tidal phases, while during the dry season, it was

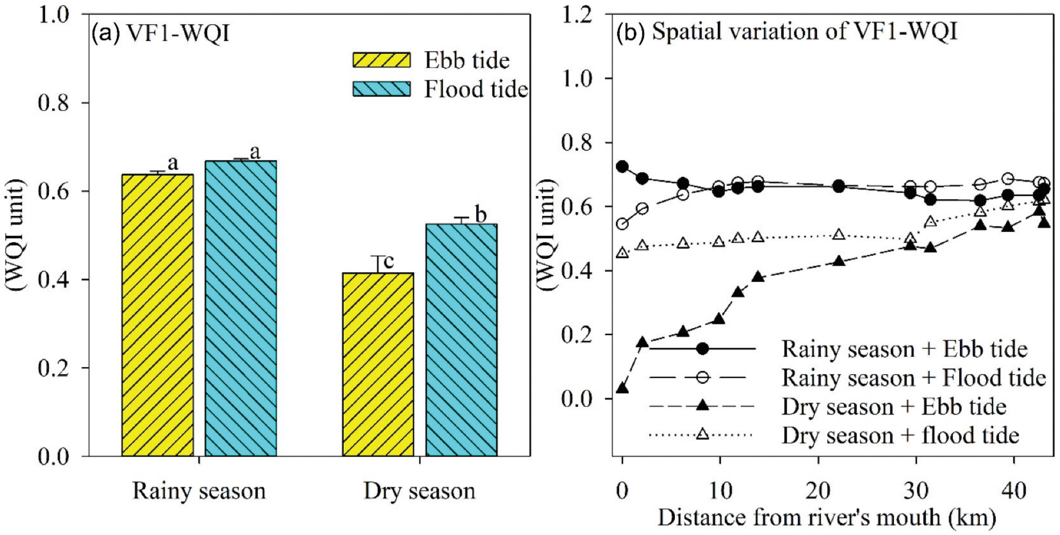

Figure 3. Componential WQI based on varimax factor 1 (VF1-WQI) in two seasons and two tidal phases (a) and spatial variation of VF1-WQI over the distance from the river's mouth (b). For panel a, the bars with the same letter are not significantly different from each other. Error bars indicate the standard deviation. The interaction effect between tidal phases and seasons is statistically significant at P ≤ 0.05.

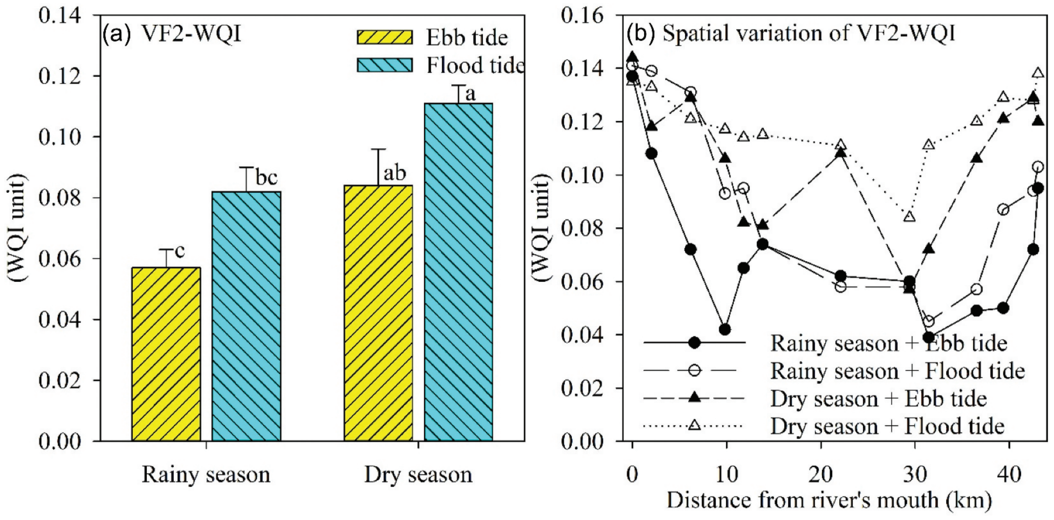

Figure 4. Componential WQI based on varimax factor 2 (VF2-WQI) in two seasons and two tidal phases (a) and spatial variation of VF2-WQI over the distance from the river's mouth (b). For panel a, the bars with the same letter are not significantly different from each other. Error bars indicate the standard deviation. The interaction effect between tidal phases and seasons is statistically non-significant at P ≤ 0.05.

significantly higher in flood tides than ebb tides (Fig. 3(a)). This meant that the interaction effect between the two experimental factors on VF1-WQI was statistically significant (P ≤ .05). The VF1-WQI of water collected during the dry season and ebb tide increased markedly from the river's mouth, while samples collected during the dry season and flood tide, as well as during the rainy season in both tidal phases, remained relatively stable across the examined length of the river (Fig. 3(b)). Among the four combinations, the dry season and flood tides exhibited the highest VF2-WQI, while the rainy season and ebb tides showed the lowest VF2-WQI (Fig. 4(a)). The change in VF2-WQI across the examined reaches of the river differed among the four combinations (Fig. 4(b)). The water from around 10 km to 30 km from the river's mouth displayed a lower VF2-WQI, while the other two ends of the river experienced a higher VF2-WQI. VF3-WQI was statistically similar between the two tidal phases during the dry season, while it was statistically higher in the flood tide than in the ebb tide during the rainy season (Fig. 5(a)), indicating a strong interaction between these two experimental factors. From the river's mouth to the other end, VF3-WQI in the rainy season and ebb tides decreased, while VF3-WQI in the rainy season and flood tides showed a slight increase (Fig. 5(b)). During the dry season, VF3-WQI slightly increased from the river's mouth to the other end during the ebb tide, while it remained relatively consistent during the flood tide. VF4-WQI was significantly lower in the ebb tide compared to the flood tide, irrespective of seasonal variation (Fig. 6(a)). During the ebb tide, VF4-WQI decreased slightly from the river's mouth to around 30

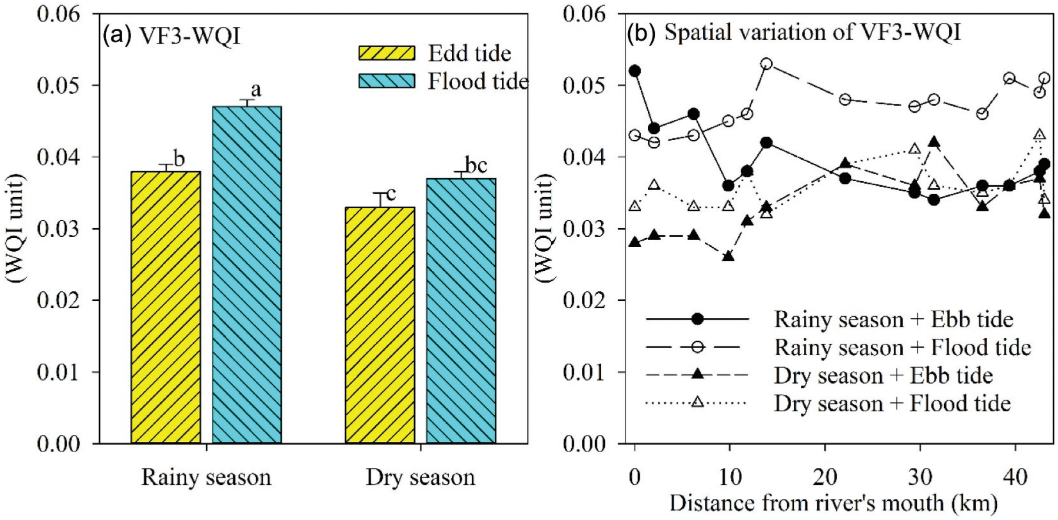

Figure 5. Componential WQI based on varimax factor 3 (VF3-WQI) in two seasons and two tidal phases (a) and spatial variation of VF3-WQI over the distance from the river's mouth (b). For panel a, the bars with the same letter are not significantly different from the other. Error bars indicate the standard deviation. The interaction effect between tidal phases and seasons is statistically significant at P ≤ 0.05.

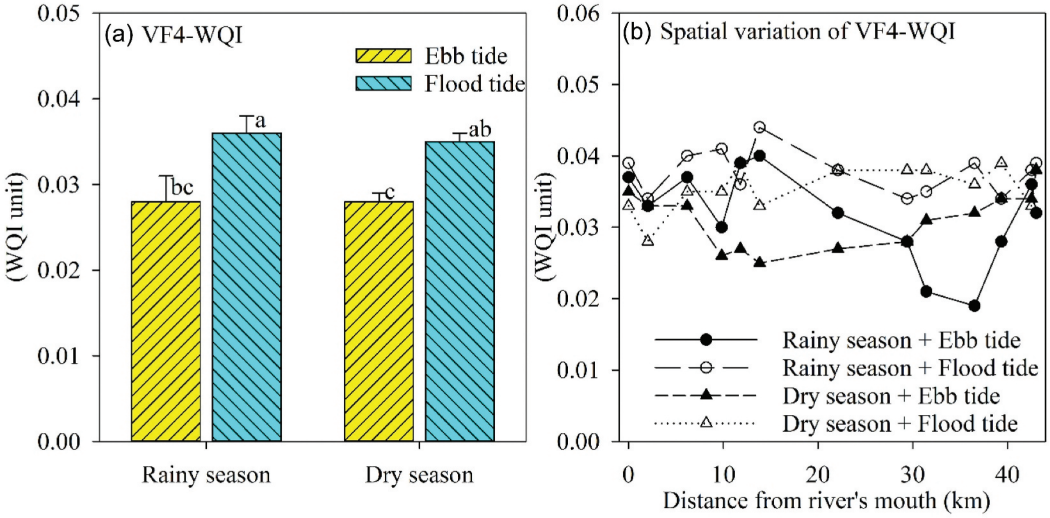

Figure 6. Componential WQI based on varimax factor 4 (VF4-WQI) in two seasons and two tidal phases (a) and spatial variation of VF4-WQI over the distance from the river's mouth (b). For panel a, the bars with the same letter are not significantly different from the other. Error bars indicate the standard deviation. The interaction effect between tidal phases and seasons is statistically non-significant at P ≤ 0.05.

Table 3. Percentage of individual pollution sources (varimax factors) and water parameters in explaining the total variance of the overall water quality index (WQI).

Pollution source		Individual parameter	
Source	Percentage	Parameter	Percentage
Varimax factor 1 (seawater intrusion)	62.68	pH	23.98
		EC	3.89
		SO_4^{2-}	10.80
		Cl^-	2.87
		Na	9.53
		K	2.81
		Ca	7.37
		Mg	1.44
Varimax factor 2 (agricultural activities)	28.54	DO	10.82
		NH_4^+-N	3.51
		Total N	4.81
		Total P	9.41
Varimax factor 3 (mixed sources)	6.76	Turbidity	1.27
		NO_3^--N	1.86
		Log(Coliform)	1.92
		Temperature	1.71
Varimax factor 4 (residential area)	2.02	BOD_5	0.12
		COD	0.09
		TSS	1.79
Error	0.03		0.03
Total	100.00		100.00

or 35 km in both seasons and then increased, while during the flood tide, this componential WQI remained stable across the examined reaches of the river (Fig. 6(b)).

3.4 Contributive percentage of individual pollution sources on surface water quality

Four varimax factors representing four primary pollution sources and their corresponding water parameters were identified and quantified to explain the variation in the water quality of the river (Table 3). Varimax factor 1, possibly involving seawater intrusion, accounted for approximately 62.68% of the total variance of the overall WQI. Among the eight water parameters strongly correlated with varimax factor 1, pH, SO_4^{2-}, and Na contributed the greatest percentage (23.98, 10.8, and 9.53%, respectively) to the total variance of the overall WQI. Two water parameters, DO and total P, which had a strong relationship with varimax factor 2, explained 10.82 and 9.41%, respectively, of the total variance of the overall WQI. The remaining seven water parameters having strong relationships with varimax factors 3 and 4 contributed a smaller proportion (less than 2%) to the total variance of the overall WQI. Collectively, the four varimax factors accounted for 62.68, 28.54, 6.76, and 2.02% of the overall WQI, respectively.

4 Discussion

4.1 Pollution sources

The PCA/FA identified four latent factors, representing the multiple-dimensional variance of the whole dataset from the current study (Table 2). Factor 1, strongly correlated with eight water parameters, Mg, EC, Cl^-, K, Ca, SO_4^{2-}, Na, and pH, likely represented a pollution source derived from seawater, which commonly contains these elements at high levels compared to freshwater. Seawater intrusion was identified as a critical factor in degrading both surface and groundwater quality (Salam and Sultana 2022, Chang *et al.* 2023, Le *et al.* 2023a). The ionic ratios of some of these parameters were also used to determine seawater intrusion in the central region of Ghana (Asare *et al.* 2021). These parameters also had significant relationships with each other (see Supplementary material, Table S1), indicating that they may come from a common source. Additionally, the componential WQI, computed from parameters having high loading values with varimax factor 1, showed lower values during the dry season than during the rainy season and was also lower in the lower reaches than in the upper reaches of the river during the dry season. This suggests that saltwater intrusion degraded the river's surface water. Likewise, seawater intrusion was identified as a significant process degrading surface water and groundwater in various regions (Ahmed and Askri, 2016, Jin *et al.* 2019, Abd-Elaty *et al.* 2021, Le *et al.* 2023a).

Four water parameters – total N, NH_4^+-N, total P, and DO – had high loading values with varimax factor 2 (Table 2), and these parameters were strongly correlated with each other (see Supplementary material, Table S1). The findings suggest that these parameters may be derived from the same source, which discharged nitrogen- and phosphorus-containing products into the river water. This source was likely associated with crop-grown areas where fertilizers and animal manure rich in nitrogen and phosphorus were used to increase crop production. During periods of high rainfall, surface runoff from agricultural fields led to soil erosion and the transportation of nitrogen- and phosphorus-containing fertilizers downstream into surface water systems (Liu *et al.* 2018, Cui *et al.* 2020). The excessive use of fertilizers, including nitrogen, phosphorus, and organic fertilizers, means that they can be carried into rivers or channels by water overflowing from fertilizer-applied areas (Bertol *et al.* 2010, Li *et al.* 2017). This process contributed to elevated concentrations of N and P in the surface water system of the Saigon River. The inverse relationship between DO and varimax factor 2 (Table 2), as well as the negative correlations between DO and total N, NH_4^+-N, and total P (see Supplementary material, Table S1), indicate that DO was reduced due to the increased oxygen demand resulting from elevated nutrient contents in water (Fernandes *et al.* 2018, Xia *et al.* 2018, Hong *et al.* 2019). Nevertheless, DO concentration can be affected by various factors (Bozorg-Haddad *et al.* 2021), complicating the explanation of DO variations in the surface water system of the current study. These findings suggest that crop production activities in the upper watershed of the Saigon River serve as a primary source for nutrient-related water parameters, which are further discussed in the following section.

Varimax factor 4 demonstrated a strong correlation with BOD_5, COD, and TSS, indicating that it represents pollution sources originating from residential areas, which commonly discharge domestic wastewater into the surrounding water system. Furthermore, these three parameters were statistically correlated with each other (see Supplementary material, Table S1), suggesting that they may come from a common source of domestic wastewater, characterized by high levels of organic substances (Koul *et al.* 2022). Consequently, the discharge of wastewater from residential areas contributed to increased levels of BOD_5, COD, and TSS in the Saigon River, leading to a reduction in VF4-WQI during the ebb tide (Fig. 6). Likewise, the discharge of municipal wastewater from residential areas was responsible for the elevated presence of organic carbon substances in the surface water system (Vega *et al.* 1998, Simeonov *et al.* 2003).

The pollution sources responsible for the remaining water parameters (turbidity, coliform, NO_3^--N, and temperature) were uncertain and potentially mixed. Turbidity might result from street dust washed into the river during rainfall, with higher levels observed during the rainy season. Increased turbidity in rainfall-runoff was attributed to degraded surface water in Jinpen Reservoir in Northwest China (Zhou *et al.* 2015). Significantly higher turbidity levels during the rainy season and ebb tide in the current study also supported this finding (Table 1). On the other hand, coliform bacteria and elevated levels of NO_3^- -N could be linked to domestic wastewater discharged from residential areas, though further research is needed for confirmation.

4.2 Factors affecting surface water quality

Overall, the surface water quality of the river was worse during the dry season than during the rainy season (Fig. 2), supporting our initial research hypothesis. This finding aligns with previous studies (Bordalo *et al.* 2001, Ameen 2019). The primary reason for this finding could be the reduced water flows and levels in the rivers during the dry season, leading to higher pollutant concentrations. In contrast, during the rainy season, increased water flow and rainfall enhanced dilution effects, resulting in lower pollutant concentrations. Moreover, the overall WQI was largely determined by the pollution sources derived from seawater intrusion, explaining 62.68% of the total variance (Table 3). Seawater intrusion, which was more pronounced during the dry season than the rainy season (Prusty and Farooq 2020), can degrade the river's water by introducing salts.

Contrary to our findings, other studies reported that water quality in rivers was higher during the dry season than during the rainy season (Hasan *et al.* 2015, Ofosu *et al.* 2021). In the case of the Densu River in Ghana, the lower WQI observed during the wet season compared to the dry season was attributed to increased agricultural practices such as agrochemical application during the rainy season (Ofosu *et al.* 2021). This explanation also aligns with the variation of the componential WQI reflecting the pollution sources from agricultural fields in the current study (Fig. 4).

The basin of the Saigon River is primarily occupied by rubber tree farms and paddy rice fields (Nguyen *et al.* 2020). These agricultural areas undergo preparation for a new crop of paddy rice or the application of agro-fertilizers to rubber tree farms at the onset of the rainy season each year. The increased water runoff during the rainy season carries agricultural residues, such as fertilizer remnants, into the rivers. This is the main reason for the notably lower componential WQI associated with agricultural sources during the rainy season compared to the dry season (Fig. 4). This finding supports our second hypothesis that componential water quality reflecting agricultural pollution sources is more degraded during the rainy season than during the dry season. Nevertheless, the overall WQI in the current study was higher during the rainy season compared to the dry season. This can be attributed to pollution sources originating from agricultural production, which ranked second after those from seawater intrusion (Table 3).

Seawater intrusion was more prevalent during the dry months (Jin *et al.* 2019), leading to relatively higher levels of certain water parameters primarily sourced from saltwater (Table 1). This accounts for a lower componential VF1-WQI during the dry season compared to the rainy season (Fig. 3). Moreover, the effects of seasonal variation depend on the tidal phase. During the rainy season, the two tidal phases have similar effects, but during the dry season, the ebb tide significantly reduces the VF1-WQI compared to the flood tide (Fig. 3). This finding does not support our third hypothesis. The timing of water sampling and the semidiurnal tide cycle of the Saigon River (Camenen *et al.* 2021) may explain this outcome. Sampling was conducted from the river's mouth towards the other end, at the onset of the ebb phase, to capture its effects. At this point, river water reached its peak level and seawater had already penetrated the river to the maximum extent after the completion of the flood tide, leading to the highest concentration of seawater-derived elements in the river water. Conversely, sampling for the flood tide effects was carried out when the tide started to rise. As a result, the proportion of seawater in the river water was at its lowest level, as the ebb tide had already transported seawater back to the sea before sampling. These findings indicate that while the flood tide transports seawater into the river, the most substantial effects of seawater intrusion were observable during the ebb tide.

The ebb tide consistently introduces pollutants from residential areas located on both sides of the river, regardless of seasonal variation. This led to higher levels of certain parameters such as BOD_5, COD, and TSS during the ebb tide than during the flood tide (Table 1). Consequently, the componential WQI representing pollution sources from residential areas was significantly lower during the ebb tide compared to the flood tide, regardless of the season (Fig. 6). These findings confirm our last hypothesis, that the ebb tide had a greater impact on degrading water quality by transporting a larger amount of domestic wastewater from residential areas into the river. Furthermore, the current study revealed a decreasing trend in VF4-WQI from the river's mouth to a distance of approximately 30 or 35 km in both seasons. This phenomenon can be attributed to the higher intensity of residential activities in the middle reaches of the river compared to the areas closer to both ends. The population density of Ho Chi Minh City was highest on both sides of the middle reaches of the Saigon River, resulting in a great discharge of domestic wastewater in this area. Consequently, during the ebb tide, there was a decrease in VF4-WQI in the middle reaches of the river compared to the other two end reaches, further reflecting the impacts of residential activities on water quality.

4.3 *Implications for water quality management strategies*

Given that water quality in the Saigon River was lower during the dry season than during the rainy season, efforts to enhance water quality should be prioritized for the dry season. The primary pollution sources contributing to the lower water quality in the river are related to seawater intrusion, which requires effective mitigation. Moreover, for coastal rivers, the tidal regime plays a crucial role in introducing salts from the sea into the rivers and transporting pollutants from residential areas located along the riverbanks. Therefore, the implementation of coastal protection measures should be prioritized to mitigate the effects of rising sea levels and reduce the risk of seawater intrusion. This could involve the construction of coastal barriers, levees, and flood control structures to prevent the intrusion of seawater into the river. Another crucial management strategy is the development of a freshwater reservoir in the upper basin of the river to maintain adequate freshwater levels, creating a push effect to prevent seawater intrusion during the dry season. By prioritizing these measures, it is possible to mitigate the adverse effects of seawater intrusion and improve the overall water quality of the Saigon River, especially during the dry season.

Meanwhile, water quality during the rainy season was primarily influenced by pollution sources derived from agricultural activities, accounting for 28.54% of the WQI of the river. Implementing best management practices, such as proper fertilizer timing and application, controlled irrigation methods, contour plowing, and buffer zones, can effectively address the pollution from agricultural production. It is also important to note that pollution sources originating from agricultural areas in the upper basin, far from the river, pose a challenge to control. A similar situation can be found in international rivers, where agricultural areas may be located far from the rivers, and strong water flow during the rainy season can transport agriculture-derived pollutants into the rivers. Managing these pollution sources requires collaboration among various sectors and neighbouring states that directly oversees the agricultural areas. In short, enhancing the water quality of coastal rivers demands a comprehensive approach that addresses seawater intrusion, agricultural practices, and residential pollution sources. Management strategies should be tailored to account for seasonal variations and the characteristics of various pollution sources.

Despite obtaining some valuable findings in the current study, certain limitations may exist. Generally, a larger dataset should be collected and analysed to draw comprehensive conclusions about natural water bodies. Thus, taking only 96 water samples across two seasons and two tidal phases might impose constraints on the study's scope. However, the primary objective of this research was to test the four hypotheses, and the current dataset is sufficient to yield statistically reliable conclusions within the context of this investigation. Another limitation is the absence of consideration of yearly variations, which is essential when quantifying water quality changes. In the context of significant climate change, fluctuations in annual rainfall, seawater intrusion, and agricultural activities may greatly impact surface water quality in rivers. Therefore, it would be beneficial to examine these variables over longer time frames. While four pollution sources were identified and quantified using the statistical analysis method, PCA/FA, a more direct examination of pollution sources at their origin would yield more accurate results. For instance, measuring water discharge from agricultural regions and residential areas would help verify the pollution sources identified through PCA/FA. Despite these limitations, the current study yielded interesting and statistically significant results that can be applied to the management of rivers with similar conditions, both domestically and internationally. The insights gained from this research may contribute to the sustainable development and effective management of such river systems.

5 Conclusions

The current study revealed substantial variations in the surface water quality of the Saigon River due to seasonal and tidal factors. Four key pollution sources were identified as contributors to the deterioration of the river's surface water quality: seawater intrusion, agricultural activities, residential areas, and a combination of multiple sources. Seawater intrusion was more prominent during the dry season due to the lack of freshwater flow, allowing seawater to encroach further into the river system. This led to a lower componential water quality index (WQI) reflecting the impacts of seawater intrusion during the dry season compared to the rainy season. Agricultural activities led to elevated levels of pollutants in the water during the rainy season, yielding a lower componential WQI reflecting the agriculture-derived sources. The effects of pollution sources derived from residential activities were more pronounced during the ebb tide than the flood tide, regardless of seasonal variation. Finally, the overall WQI was substantially lower during the dry season than during the rainy season, with seawater intrusion being the primary determining factor. This source accounts for a substantial proportion of 62.68% of the total variance in the overall WQI. The second major contributor was pollution sources from agricultural activities, which explained 28.54%. These pollution sources were identified, quantified, and fractionated through the utilization of the statistical method of principal component analysis/factor analysis (PCA/FA). This approach allowed for the segregation of various pollution sources from a comprehensive dataset, enabling a detailed assessment of the impacts of specific anthropogenic activities, depending on natural factors such as seasonal variation and tidal phase. The interactions of these factors possibly determine the surface water quality of coastal river systems worldwide. Consequently, the findings emphasize the importance of implementing effective management strategies to mitigate pollution sources, tailoring them to seasonal variation and tidal phases to improve the overall water quality of coastal rivers and foster sustainable development.

Acknowledgements

The authors thank the Industrial University of Ho Chi Minh City (IUH), colleagues, and students at the Institute of Environmental Science, Engineering and Management (IESEM-IUH) for providing support for this research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the Industrial University of Ho Chi Minh City (IUH) under grant number 108/HD-DHCN.

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