



# Unveiling the interactive effects: seasonal variations and pollution sources shaping the quality of surface water system in Khanh Hoa, Vietnam

Thang Viet Le<sup>1</sup> · Binh Thanh Nguyen<sup>1</sup>

Accepted: 19 February 2025

© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2025

## Abstract

While numerous studies have examined pollution sources and seasonal effects on surface water quality independently, the complex interactions between these factors remain understudied. This research aimed to fractionate and quantify pollution sources and examine their interactive effects with seasonal variations on surface water quality in Khanh Hoa, Vietnam. The current study was based on 1080 surface water samples taken from three common water bodies - lakes, rivers, and canals across dry and rainy seasons and analyzed for 13 physiochemical properties. Findings revealed that surface water quality was influenced by four primary pollution sources: agricultural activities, residential areas, onsite erosion, and climatic factors. Agricultural sources dominated canal water quality (93.0–94.7%) but had less impact on lakes and rivers (12.8–23.8%). Residential sources significantly affected lakes and rivers (30.23–32.66%) but minimally influenced canals (2.6–5.6%). Onsite erosion sources had greater impacts on lakes and rivers typically during the rainy season and exhibited minimal impacts on canals. Lakes and rivers maintained consistent and higher water quality across seasons (water quality index (WQI) 9.1 to 9.3 out of 1.0 – excellent), while canals exhibited substantially lower quality in the dry season (WQI 0.75) compared to the rainy season (WQI 0.78). These interactive impacts were mitigated by self-purification, water residence time in lakes and rivers, dilution effects, and fast pollutant transport in canals. Our findings highlight the importance of effective management of these key pollution sources in interaction with seasonal variation for maintaining water quality and ensuring environmental sustainability.

**Keywords** Agricultural pollution sources · Dry season · Rainy season · Residential pollution sources · Water body

## 1 Introduction

Recently, Jia et al. (2021) reported that surface water in lakes is more polluted during the rainy season than during the dry season. Similarly, specific water quality parameters such as biological oxygen demand ( $BOD_5$ ), dissolved oxygen (DO), total suspended solids (TSS), and coliforms were noted to be higher in the rainy season compared to the dry season (Ly and Giao 2018). In contrast, other studies have

found that surface water quality was significantly lower during the dry season than during the rainy season (Woldeab et al. 2018); Gomes et al. (2019) found that some water bodies showed better quality while others exhibited lower quality in the same season. There could be many reasons explaining the diverse findings among these studies. Moreover, Nguyen et al. (2020) observed that the impact of seasonal variation on surface water quality is dependent on pollution sources. These findings suggest that, apart from seasonal fluctuations, the nature of pollution sources and their interaction could be the primary factors contributing to the disparities observed in these studies, which are insufficiently discussed in the literature.

While the surface water system holds significance for various reasons (Bănăduc et al. 2022; Ringler et al. 2022), the rapid growth of population and urbanization, especially in developing nations, is causing the gradual degradation

---

✉ Binh Thanh Nguyen  
nguyenbinh@iuh.edu.vn

<sup>1</sup> 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, Vietnam

of this system (Bhateria and Jain 2016; Ma et al. 2022). In a particular region, the surface water system may include a few main types of water bodies such as rivers, lakes, and canals, serving as vital water resources for domestic, industrial, agricultural, and recreational purposes. Additionally, it plays a role in collecting wastewater discharged from various human activities (Giao and Ly 2023; Nguyen et al. 2021; Reda 2019). The utilization of surface water resources, such as for irrigation or human consumption, hinges on their quality, which is influenced by pollution sources (Zhang et al. 2023). These sources may originate from human activities such as residential, industrial, urban, and agricultural practices, as well as natural processes like seasonal variation, changes in rainfall, land surface erosion, and sediment transport (Anh et al. 2023; Müller et al. 2020; Qadir et al. 2008; Wang et al. 2023). Different pollution sources exhibit distinct characteristics in their impacts on surface water systems. For example, pollution sources derived from agricultural activities may elevate nutrient parameters such as  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ , and P in the surface water due to inorganic fertilizer application, while residential areas introduce organic pollutants by discharging blackwater to surface water systems (Rashmi et al. 2020; Vadde et al. 2018; Xia et al. 2020). It is crucial to identify and quantify these pollution sources to effectively develop management strategies for maintaining the high quality of surface water systems.

Moreover, the impacts of diverse pollution sources are contingent upon seasonal variations, typically characterized by dry and rainy seasons (Dey et al. 2021). Various pollution sources may release a substantial volume of pollutants into the surrounding environment, and these pollutants are subsequently transported to various water bodies via water flow, a process influenced by seasonal changes. Heavy rainfall in the wet season can carry pollutants over significant distances from their origins to larger water bodies like lakes and rivers. Consequently, lakes and rivers may exhibit higher pollution levels during the rainy season than during the dry season (Jia et al. 2021). Conversely, minimal rainfall and great water evaporation in the dry season may result in a greater accumulation of pollutants in proximity to their sources, particularly in canals. Canals, being narrow waterways, commonly collect pollutants directly from their sources, leading to increased pollution during the dry season. These imply that the influence of human activities, manifested through anthropogenic pollution sources, on the quality of surface water systems may depend on natural factors like seasonal variations, warranting further research.

To comprehensively assess the interaction effects of pollution sources and seasonal variation, it is crucial to establish a study in a region featuring various water bodies of canals, rivers, and lakes, which can be commonly found in inland water systems (Némethy et al. 2022). In general,

lakes and large inland water bodies receive water from various sources, including rivers and canals and others such as precipitation, runoff, and underground springs. The inflow from rivers and canals introduces sediments, nutrients, and pollutants, thereby influencing the water quality of lakes (Kuriata-Potasznik et al. 2020). Rivers, as naturally flowing watercourses, flow toward oceans, seas, lakes, and other rivers, while canals are artificial waterways or channels constructed to convey water for various purposes, such as irrigation, drainage, and the collection of wastewater from various pollution sources. These typical water bodies are susceptible to pollution at different levels depending on pollution sources and seasonal fluctuation. Therefore, the current study was conducted in Khanh Hoa province, Vietnam, as a case study with objectives of (1) fractionating and quantifying pollution sources and (2) examining their interactive effects with seasonal variations on the surface water quality of the study area. This particular region is predominantly characterized by mountainous terrain, with a narrow delta constituting less than one-tenth of its total area. The region has a complex surface water system, including numerous lakes, and short and steep rivers, as well as canals designed for irrigation and wastewater collection.

## 2 Materials and methods

### 2.1 Study area

The current study was undertaken in Khanh Hoa province, Vietnam, spanning from  $11^{\circ}48'22''$  to  $12^{\circ}52'39''$  N and  $108^{\circ}40'8''$  to  $109^{\circ}27'50''$  E with various study stages shown in Supplementary Fig. 1. Covering a natural area of 5,137.8 km<sup>2</sup>, the province had a population of more than 1,232,000 people as of April 1, 2019, resulting in a population density of 238 people/km<sup>2</sup> (Khanh Hoa statistics offices 2020). For comparison, in the same year, the entire territory of Vietnam had a population density of approximately 291 people/km<sup>2</sup>. Khanh Hoa, positioned as a coastal province in South Central Vietnam, lies near the Truong Son mountain range, featuring a rugged topography characterized by numerous mountains and a network of short, steep rivers and streams (Donre 2020). Khanh Hoa province experiences a tropical ocean monsoon climate, with an average annual temperature of 26.7 °C (Le and Nguyen 2023). Temperature fluctuations follow a seasonal pattern, peaking in the dry season and declining in the rainy season. Annual rainfall varies from 1,270 to 1,762 mm, strongly influenced by both season and terrain. The rainy season spans four months, from September to December, contributing 60–80% of the total rainfall, while the dry season lasts eight months, from January to August each year (Donre 2020).

Khanh Hoa province boasts essential continental surface water resources, including rivers, streams, canals, and lakes, catering to residential, industrial, agricultural, and energy-related purposes. The entire province has 31 reservoirs, comprising 28 irrigation lakes and 3 hydroelectric lakes. With approximately 40 rivers exceeding 10 km, Khanh Hoa has a robust internal water network. Notably, four significant rivers, Cai, Dinh, Suoi Dau, and To Hap play crucial roles in the socio-economic development of the region. Additionally, the study region possesses a network of canals serving various purposes such as drainage, irrigation, transportation, and wastewater collection.

## 2.2 Experimental setup

The surface water resources in Khanh Hoa Province are subject to varying influences from both natural factors like temperature and rainfall (seasonal variation), and human activities. These human factors involve the intake and discharge of wastewater from residential activities, agriculture, fisheries, industry, transportation, tourism, and services. Consequently, the current study focused on three types of water bodies, lakes, rivers, and canals in the region. Lakes are relatively large reservoirs, storing water with pollutants derived from various sources, while canals are narrow waterways mainly collecting and transporting water and pollutants from their sources. Eighteen sampling sites, 7 sites on lakes, 8 sites on rivers, and 3 sites on canals (Supplementary Fig. 2) were pre-selected for surface water sampling in both dry and rainy seasons. Therefore, seasonal variation is one experimental factor contributing to the determination of the quality of the surface water system (three water bodies) in the current study. Water body reflecting pollution sources was another experimental factor examined in the current study.

## 2.3 Water sampling and water quality analysis

The current study involved the collection of surface water samples from 18 pre-selected sites over 5 consecutive years, from 2016 to 2020. Sampling was conducted in two seasons, covering all 12 months each year, making a total of 1080 surface water samples (18 sites/month x 12 months/year x 5 years). At each sampling site, the Van Dorn water sampler was employed to collect 8 sub-samples from the 0–50 surface layer into a 20-liter bucket. From the bucket, approximately 4 L of water were taken and transferred into a plastic jar with a secure lid, which was then placed in an ice box at 4 °C. The remaining water in the bucket was directly measured for pH using a pH meter (Thermo Scientific™ Orion™ 3-Star Benchtop pH Meter, USA), temperature using a thermometer, turbidity using a spectrophotometer (Hach DR/2010 spectrophotometer, USA), and dissolved oxygen (DO) using the DO meter (Oxi 3210 portable dissolved oxygen Meter, USA) (Table 1). The water-containing jars were then promptly transported to the laboratory for analysis of 9 key water quality parameters, including  $\text{Cl}^-$ ,  $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and  $\text{PO}_4^{3-}$ , biochemical oxygen demand ( $\text{BOD}_5$ ), chemical oxidation demand (COD), total suspended solids (TSS), and total coliform. These analyses were carried out based on the national standard methods QCVN 08-MT:2015/BTNMT (Monre 2015) and the methods outlined in the previous study (Nguyen et al. 2019). The  $\text{Cl}^-$  concentration was specifically determined using the titration method (Hajrasuliha et al. 1991).

## 2.4 Statistical analysis

Principal component analysis/factor analysis (PCA/FA) with a detailed description shown in Supplementary Text 1 was applied to the whole dataset of 13 water parameters over five years to fractionate and quantify pollution sources (Chidiac et al. 2023; Pati et al. 2023). In brief, PCA/FA

**Table 1** Averaged values and standard deviation (SD) of 13 measured water parameters in five years

Parameters	2016		2017		2018		2019		2020	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Temperature (°C)	29.35	2.65	28.99	2.77	29.10	2.62	29.38	1.67	29.57	1.84
pH	7.53	0.45	7.25	0.51	7.50	0.46	7.43	0.39	7.40	0.43
Turbidity (NTU)	16.20	19.07	8.94	19.78	29.85	40.89	20.05	24.35	29.25	41.96
DO ( $\text{mg L}^{-1}$ )	5.28	1.03	5.52	1.04	5.55	1.31	5.29	0.96	5.30	0.95
TSS ( $\text{mg L}^{-1}$ )	21.31	27.00	21.22	26.30	21.12	26.65	21.20	31.75	20.41	23.19
$\text{BOD}_5$ ( $\text{mg L}^{-1}$ )	7.25	13.61	6.66	11.57	5.86	7.09	7.47	2.14	7.66	5.46
COD ( $\text{mg L}^{-1}$ )	14.61	27.03	12.10	20.89	10.19	12.31	12.57	3.52	13.22	9.16
$\text{Cl}^-$ ( $\text{mg L}^{-1}$ )	31.33	80.15	26.48	69.34	38.86	107.82	32.43	95.89	33.45	90.04
$\text{NH}_4^+$ ( $\text{mg L}^{-1}$ )	0.72	3.12	0.71	2.09	0.56	1.75	0.69	1.90	0.68	1.80
$\text{NO}_3^-$ ( $\text{mg L}^{-1}$ )	0.25	0.45	0.31	0.44	0.31	0.53	0.19	0.39	0.15	0.40
$\text{NO}_2^-$ ( $\text{mg L}^{-1}$ )	0.03	0.07	0.03	0.09	0.03	0.11	0.04	0.13	0.02	0.04
$\text{PO}_4^{3-}$ ( $\text{mg L}^{-1}$ )	0.25	0.67	0.25	0.65	0.24	0.70	0.22	0.64	0.10	0.24
Coliform ( $\text{Log}(\text{MPN } 100 \text{ ml}^{-1})$ )	2.02	1.64	1.71	1.25	1.09	1.15	1.34	1.02	0.59	0.90

was applied using the JMP application (JMP pro 17, SAS Institute Inc, NC, USA), based on the varimax rotation method, which is recommended for obtaining orthogonal rotation variables (latent factors) (Pati et al. 2023). Latent factors with eigenvalues greater than 1 (representing more explained variance than a single original variable) were retained. Original variables with high loadings (absolute values greater than 0.5) on a specific factor were considered to be strongly associated with that factor and were used to interpret its meaning.

Analysis of variance (ANOVA) was performed based on a completely random 2-factor model after confirming the homogeneity of variance and normal distribution. Tukey's Honest Significant Difference test was employed to discern differences between means when ANOVA results indicated significant differences at  $P \leq 0.05$ .

The WQI was calculated from 13 parameters based on the results of PCA/FA analysis (Le et al. 2023a), according to Eq. 1 (Eq. 1). The WQI has a scale ranging from 0.00 to 1.00, where 1 indicates excellent quality.

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

where  $n$  is the number of parameters;  $w_i$  is the weightage of the  $i^{\text{th}}$  parameter and  $s_i$  is the score of the  $i^{\text{th}}$  parameter. The values of  $w_i$  were determined by the results of PCA/FA analysis (Table 2) and the values of  $s_i$  were determined based on the method by (Le et al. 2023b). Thirteen parameters were divided into 3 groups including the "more is better" group, "less is better" group, and "optimal" group. The groups "more is better," "less is better," and "optimal" indicate that within each group, a parameter is considered better

**Table 2** Correlation coefficients of surface water parameters with latent factors from principal component analysis/factor analysis.

Water parameters	Fac-tor 1	Fac-tor 2	Fac-tor 3	Fac-tor 4	Parameter weight-age ( $w_i$ )
$\text{PO}_4^{3-}$	<b>0.83</b>	0.33	0.08	0.07	0.13
$\text{NO}_2^-$	<b>0.82</b>	-0.01	0.09	-0.14	0.13
$\text{NO}_3^-$	<b>0.82</b>	-0.03	0.07	-0.21	0.13
$\text{Cl}^-$	<b>0.77</b>	0.35	0.01	0.12	0.13
$\text{NH}_4^+$	<b>0.62</b>	0.38	-0.06	0.24	0.13
COD	0.14	<b>0.90</b>	0.09	0.04	0.05
$\text{BOD}_5$	0.16	<b>0.90</b>	0.10	0.04	0.05
Log(coliform)	0.14	<b>0.58</b>	-0.07	-0.20	0.05
Turbidity	-0.07	-0.03	<b>0.90</b>	0.08	0.04
TSS	0.25	0.14	<b>0.83</b>	-0.16	0.04
DO	-0.56	<b>-0.55</b>	-0.09	-0.22	0.05
Temperature	0.03	0.15	0.02	<b>0.73</b>	0.03
pH	-0.04	-0.22	-0.08	<b>0.69</b>	0.03
Eigenvalue	4.67	1.62	1.52	1.20	
Percent	35.95	12.49	11.71	9.26	
Cumulative Percent	35.95	48.44	60.15	69.41	
Factor weightage	0.52	0.18	0.17	0.13	

Bold numbers are those greater than 0.5.

at higher levels, lower levels, and optimal levels, respectively. The "more is better" group includes DO; the optimal group includes pH and the "less is better" group includes the remaining 11 parameters. For the "more is better" and "neutral" groups, the  $s_i$  value was calculated according to Eq. 2 (Eq. 2).

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

For the "less the better" group,  $s_i$  was determined based on Eq. 3 (Eq. 3).

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

Where  $x_i$ ,  $x_{min}$ , and  $x_{max}$  were the analytical, minimum, and maximum values of parameter  $i$ , respectively. The componential water quality indexes (componential WQIs) reflecting each of the four pollution sources identified by PCA/FA were computed based on the method by (Le et al. 2023a). In addition, multiple linear regression analysis was undertaken to quantify the contribution of four factors, associated with four potential pollution sources, derived from PCA/FA analysis to the overall WQI index (Putri et al. 2018).

## 3 Results

### 3.1 Principle component analysis/factor analysis (PCA/FA)

The averaged values of the 13 water parameters in five years were shown in Table 1. The application of PCA/FA showed that four varimax factors, each possessing an eigenvalue exceeding 1, were extracted that together explained 69.41% of the total variance of the whole dataset (Table 2 and Supplementary Fig. 3). Factor 1 explained 35.95% of the total variance, followed by factor 2 (12.49%), factor 3 (11.71%), and factor 4 (9.26%). The most important factor, factor 1, had high loading values (exceeding 0.5) with five parameters, including  $\text{PO}_4^{3-}$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ , and  $\text{NH}_4^+$ . Factor 2 displayed high correlation coefficients with four parameters, including  $\text{BOD}_5$ , COD, Log(coliform), and DO. Similarly, Factor 3 demonstrated a strong correlation with 2 parameters of turbidity and TSS, and Factor 4 exhibited a noteworthy correlation with temperature and pH. The interrelationships among the 13 water parameters were shown in Supplementary Table 1.

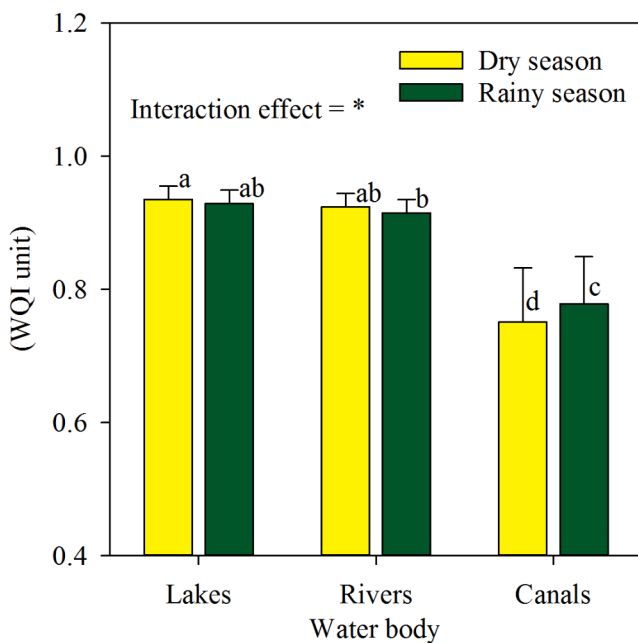
### 3.2 Overall surface water quality index (WQI)

The WQI exhibited the highest values in the lakes (0.93 and 0.93 units), followed by rivers (0.92 and 0.91 units), and canals (0.75 and 0.78 units out of a scale of 1.00 excellent)

in dry and rainy seasons, respectively (Fig. 1). A significant interaction between water bodies and the seasons was observed on WQI. Although the WQI remained relatively consistent between the two seasons in lakes and rivers, a significant difference was observed between the two seasons in canals. Specifically, the WQI in canals was statistically significantly lower during the dry season, compared to the rainy season, based on two-way ANOVA with  $p \leq 0.05$ .

### 3.3 Water quality parameters of the four PCA/FA factors

Figure 2 shows the componential WQI reflecting factor 1 (WQI1) and water parameters having high loading values with factor 1. A significant interaction between water bodies and seasons was observed for WQI1. In lakes and rivers, WQI1 remained consistent between the dry and rainy seasons (around 0.65 units), while the dry season exhibited a lower WQI1 (0.52 units) than the rainy season (0.54 units). The water parameters associated with Factor 1, such as  $\text{NH}_4^+$  (Fig. 2b),  $\text{NO}_3^-$  (Fig. 2c),  $\text{NO}_2^-$  (Fig. 2d),  $\text{PO}_4^{3-}$  (Fig. 2e), and  $\text{Cl}^-$  (Fig. 2f) had higher levels in canals than in the other water bodies.  $\text{NH}_4^+$  levels varied from 0.3 to 0.6 ( $\text{mg L}^{-1}$ ) in lakes and rivers, and from 3.54 to 4.01 ( $\text{mg L}^{-1}$ ) in canals. Similarly, canals exhibited the highest levels of  $\text{NO}_3^-$  (0.70 and 0.63  $\text{mg L}^{-1}$ ),  $\text{NO}_2^-$  (0.12 and 0.13  $\text{mg L}^{-1}$ ),  $\text{PO}_4^{3-}$  (0.15 and 0.08  $\text{mg L}^{-1}$ ), and  $\text{Cl}^-$  (181.7 and 113.9  $\text{mg L}^{-1}$ ), in the dry and rainy seasons, respectively, compared to



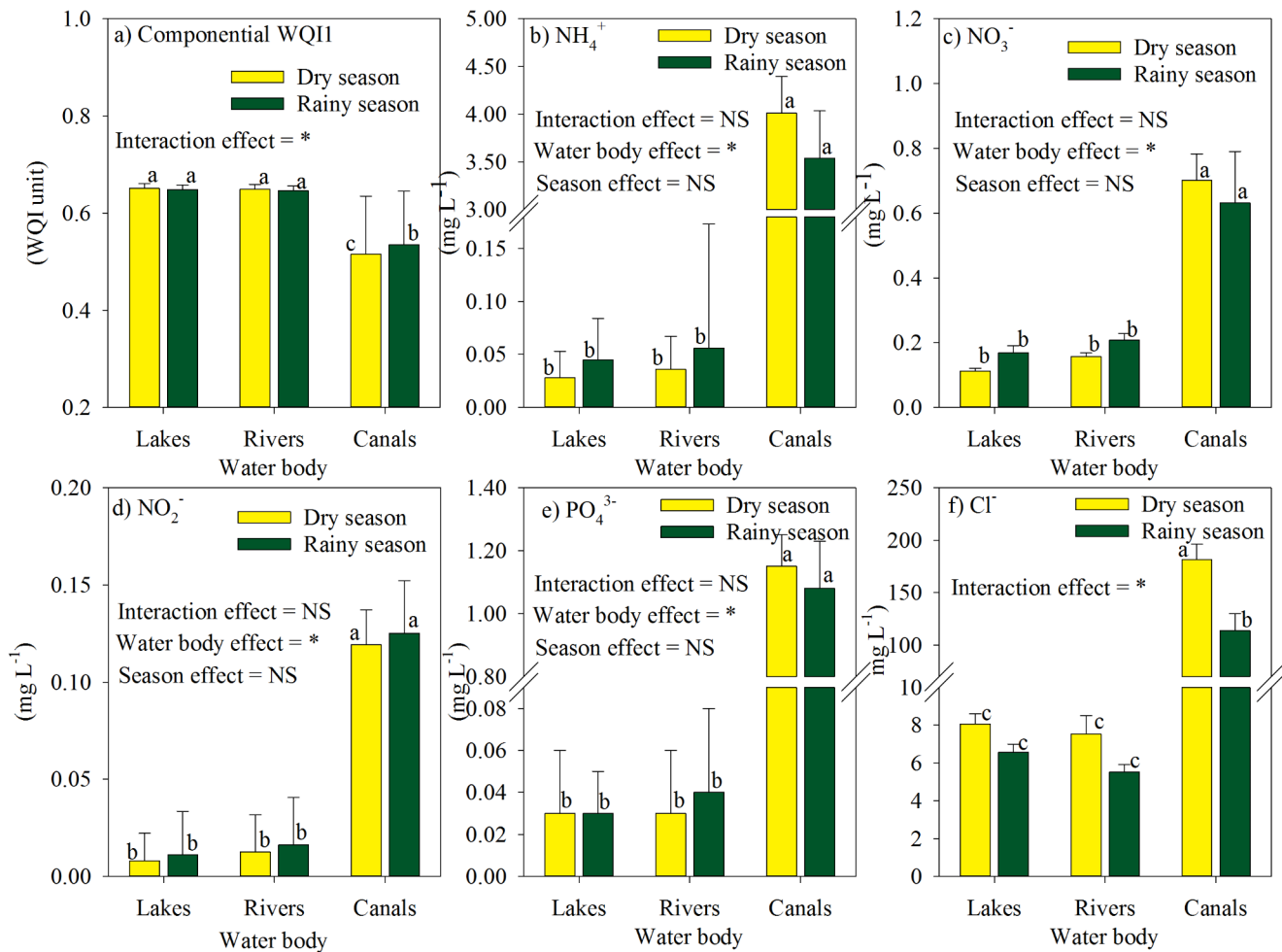
**Fig. 1** The overall water quality index (WQI) of surface water collected from three main water bodies in two seasons. Error bars indicate the standard deviation of the mean. Bars attached with the same letters are not significantly different from each other. \* indicates the effect is significant

the other two water bodies. In lakes and rivers,  $\text{NO}_3^-$  varied from 0.11 to 0.21  $\text{mg L}^{-1}$ ;  $\text{NO}_2^-$  ranged from 0.01 to 0.02  $\text{mg L}^{-1}$ ,  $\text{PO}_4^{3-}$  from 0.03 to 0.04  $\text{mg L}^{-1}$ , and  $\text{Cl}^-$  from 5.52 to 8.07  $\text{mg L}^{-1}$ . In canals, the  $\text{Cl}^-$  concentration was significantly lower during the rainy season (113.95  $\text{mg L}^{-1}$ ) than the dry season (181.7  $\text{mg L}^{-1}$ ), while no significant seasonal difference was observed in lakes and rivers.

The componential WQI reflecting factor 2 (WQI2) and water parameters exhibiting strong correlations with factor 2 were shown in Fig. 3. WQI2 values were significantly higher in lakes (0.169 and 0.171 units) and rivers (0.161 and 0.166 units), compared to canals (0.121 and 0.132 units, for the dry and rainy seasons, respectively). In rivers and canals, WQI2 was significantly lower in the dry season than in the rainy season, while lakes exhibited similar WQI2 between the two seasons. The water parameters associated with factor 1, COD,  $\text{BOD}_5$ , and log(coliform), were notably higher in canals than in the other two water bodies. COD values varied from 8.02 to 9.84  $\text{mg L}^{-1}$  in lakes and rivers, escalating to 23.7 to 35.3  $\text{mg L}^{-1}$  in canals.  $\text{BOD}_5$  levels ranged from 4.52 to 5.34  $\text{mg L}^{-1}$  in lakes and rivers and 13.73 to 19.65  $\text{mg L}^{-1}$  in canals. In lakes and rivers, these parameters exhibited no significant seasonal variation, while canals showed significant differences between the dry and rainy seasons. Log(coliform) values changed from 0.41 to 1.60 units in lakes and rivers and from 0.42 to 0.92 units in canals. This parameter was significantly higher in the dry season than in the rainy season across all three water bodies. DO levels in canals were significantly lower than in other water bodies and seasonal variation caused no significant effects on this parameter.

The componential WQI reflecting factor 3 (WQI3) and its associated water parameters were shown in Fig. 4. Lakes exhibited the highest WQI3 (0.081 and 0.078 units), while canals had the lowest values (0.075 and 0.071 units) and the dry season showed a higher WQI3 than the rainy season. The levels of turbidity and TSS were lower in the dry season than in the rainy season. Turbidity levels varied among the three water bodies, with rivers showing the highest values (21.0 and 38.5 NTUs) and lakes having the lowest (12.0 and 20.9 NTUs). Conservely, TSS concentrations were highest in canals (32.7 and 42.8  $\text{mg L}^{-1}$ ) and lowest in lakes (7.9 and 12.5  $\text{mg L}^{-1}$ ).

The componential WQI associated with factor 4 (WQI4) displayed a notable increase from lakes (0.034 and 0.032 units) to rivers (0.037 and 0.033 units) and canals (0.039 and 0.040 units) (Fig. 5a). The dry season showed a significantly higher temperature, averageing 29.63 °C, than the rainy season (28.99 °C) (Fig. 5b). Canals exhibited a higher temperature than the other two water bodies. Canals also exhibited the lowest pH level (7.21), while lakes showed the highest pH value (7.66) (Fig. 5c).



**Fig. 2** Componential WQI and its associated water quality parameters in three water bodies and two seasons. Error bars indicate the standard deviation of the mean. Within a panel, bars attached with the same let-

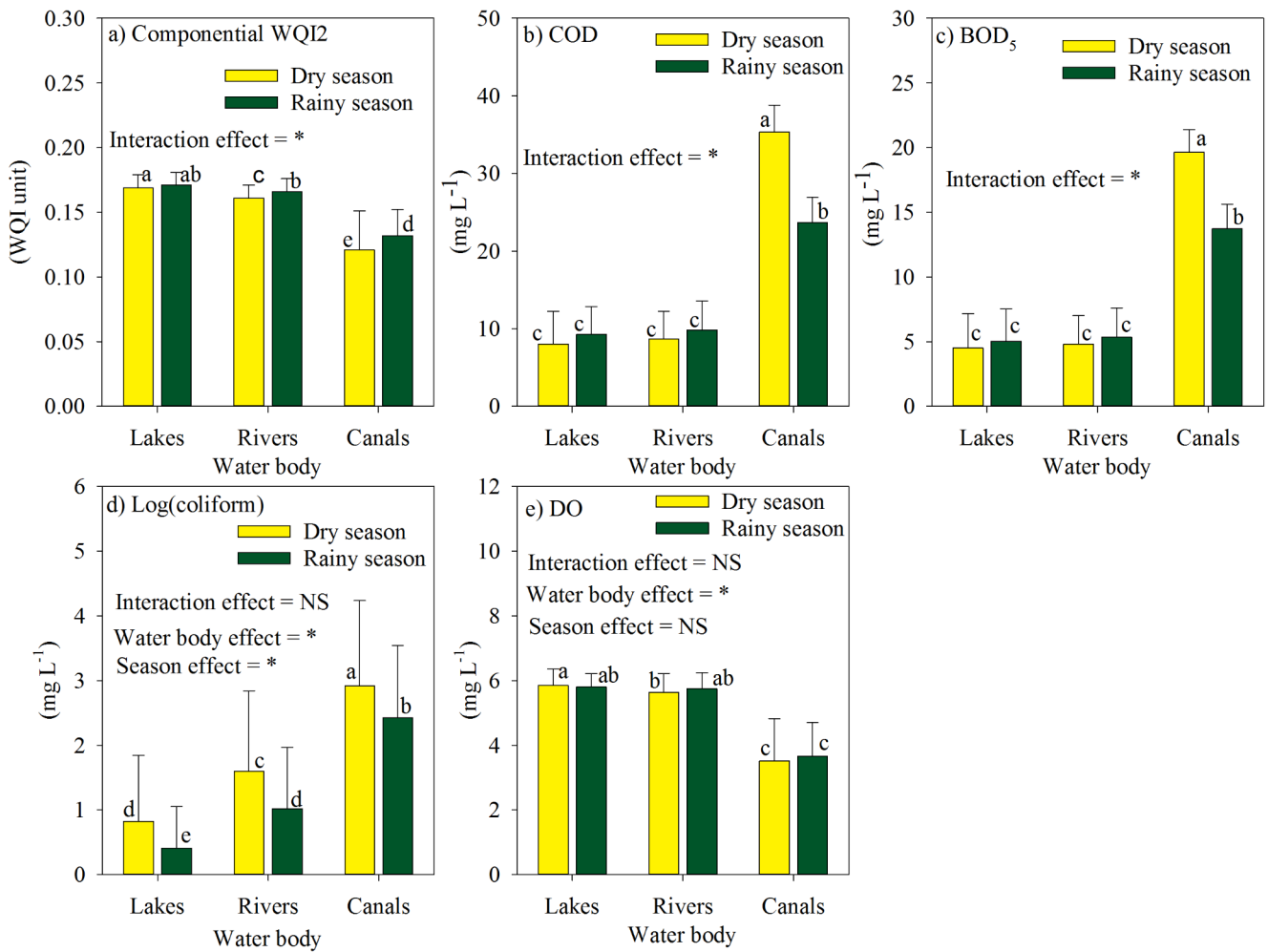
ters are not significantly different from each other. \* and NS indicate the associated effect is significant and insignificant, respectively

The multiple regression analysis showed that the overall WQI was significantly correlated with all four componential WQIs (Table 3). In lakes and rivers, the componential WQI2 explained the highest total variance in the overall WQI during the dry season – 30.23% for lakes and 32.66% for rivers. Conversely, during the rainy season, componential WQI3 explained the greatest variance in the overall WQI – 49.55 for lakes and 46.25% for rivers. For canals, the componential WQI1 accounted for the highest proportion of the overall WQI during both dry (93.02%) and rainy (94.96%) seasons. Specifically, factor 1-based componential WQI1 was important in determining the overall WQI for surface water in canals in both seasons. Additionally, factor 2-based componential WQI1 was significant for lakes and rivers during the dry season, while factor 3-based componential WQI3 was important for lakes and rivers during the rainy season.

## 4 Discussion

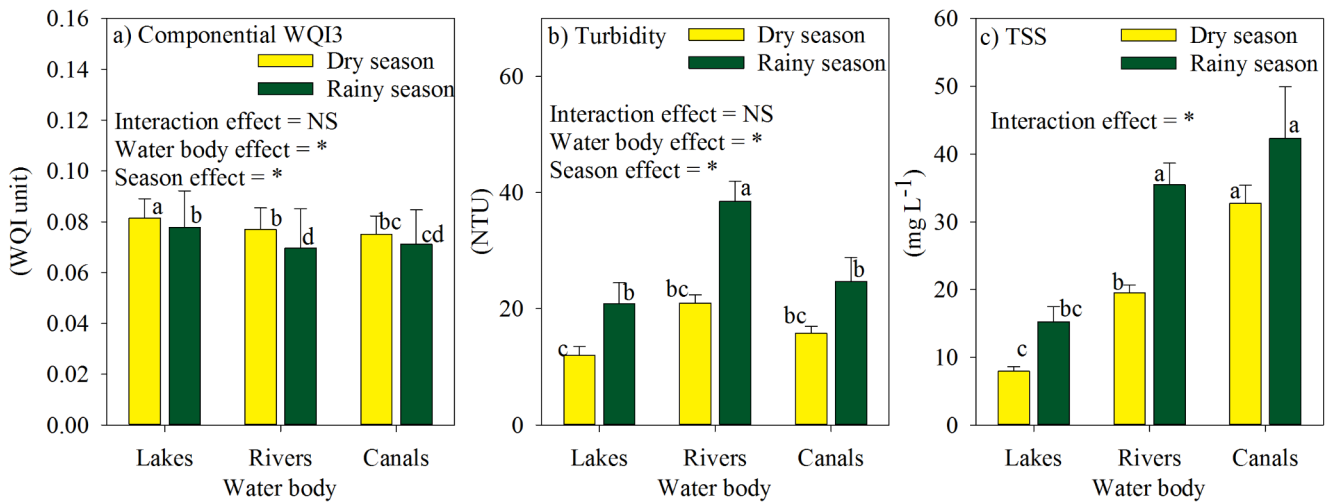
### 4.1 Pollution sources

Principal component analysis/factor analysis revealed four key latent factors (Tables 2 and 3) driving the total variance in the whole dataset. These factors represented the primary pollution sources exerting the most significant influences on the 13 surface water quality parameters analyzed in the present study. The primary contributor to variations in  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ , and  $\text{PO}_4^{3-}$  appears to be agricultural production, including both crop and livestock activities. Notably, these parameters having significant inter-relationships (Supplementary Table 1), additionally suggested that these could come from a common source. The application of organic and inorganic fertilizers in crop production released a large amount of P and N into the environment (Berger et al. 2022; Liu et al. 2021). Livestock wastewater is known for its high nutrients and organic matter contents (Hu et al.



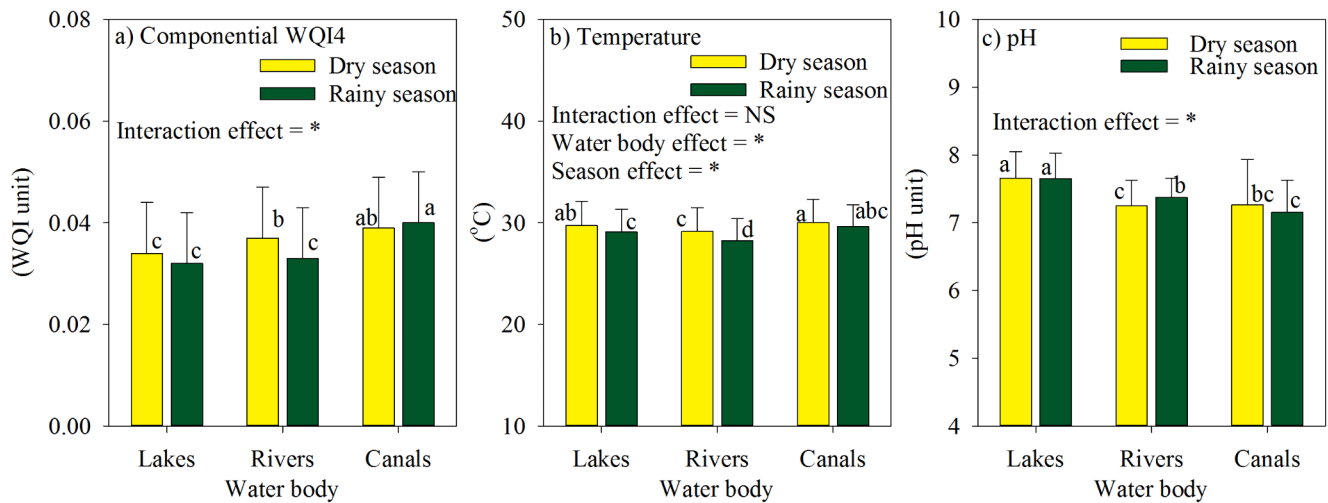
**Fig. 3** Componential WQI2 and its associated water quality parameters in three water bodies and two seasons. Error bars indicate the standard deviation of the mean. Within a panel, bars attached with the same let-

ters are not significantly different from each other. \* and NS indicate the associated effect is significant and insignificant, respectively



**Fig. 4** Componential WQI3 and its associated water quality parameters in three water bodies and two seasons. Error bars indicate the standard deviation of the mean. Within a panel, bars attached with the same let-

ters are not significantly different from each other. \* and NS indicate the associated effect is significant and insignificant, respectively



**Fig. 5** Componential WQI4 and its associated water quality parameters in three water bodies and two seasons. Error bars indicate the standard deviation of the mean. Within a panel, bars attached with the same let-

ters are not significantly different from each other. \* and NS indicate the associated effect is significant and insignificant, respectively

**Table 3** Percentage of individual componential WQIs computed based on PCA/FA in explaining the total variance of the overall WQI of three water bodies and two seasons.

Componential WQIs	Lakes		Rivers		Canals	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
WQI1	12.86*	21.75*	23.39*	19.12*	93.02*	94.96*
WQI2	30.23*	8.49*	32.66*	16.82*	5.65*	2.62*
WQI3	17.8*	49.5*	17.24*	46.25*	0.3*	1.62*
WQI4	18.76*	10.5*	15.18*	8.49*	0.73*	0.52*
Error	20.34	9.76	11.53	9.32	0.29	0.28
Total variance	100.00	100.00	100.00	100.00	100.00	100.00

\* indicates the effect of the associated componential WQI is significant at  $P < 0.05$ .

2020). These pollution sources contribute to elevated nutrient-related parameters in surface water resources through runoff from crop fields and livestock areas. Wastewater from aquaculture, rich in nutrients, organic matter, oil, and grease resulting from excess food and feces (Coldebella et al. 2017; Dauda et al. 2019; Romano and Zeng 2013) also poses potential impacts on nutrient-related parameters in receiving water bodies. As for  $\text{Cl}^-$ , given the considerable distance of the water system, especially canals, from the sea in the study area, it can be assumed that salinity intrusion from the sea has no obvious impact on the sampling sites. On the other hand, agricultural application of organic manure or animal wastes, which were rich in  $\text{Cl}^-$  (Geilfus 2019), may contribute to the  $\text{Cl}^-$  concentration in the surface water system of the study area.

Four parameters, COD,  $\text{BOD}_5$ , Log(coliform), and DO displaying high loading values with factor 2 (Table 2), may share a common source derived from residential areas. Residential areas contribute greatly to surface water pollution as domestic wastewater introduces large amounts of organic matter, suspended solids, and pathogenic bacteria (Jiao 2021). Especially, the discharge of black water, known for

its richness of organic compounds (Islam 2023), contributes to the increase of organic carbon-based parameters in the water system in the current study. The presence of elevated levels of organic compounds, as indicated by COD and  $\text{BOD}_5$ , leads to increased consumption of dissolved oxygen through biological oxidation-reduction processes, thereby reducing DO levels in surface water systems (Azha et al. 2023; Hong et al. 2019; Xia et al. 2018).

The third pollution source, affecting turbidity and TSS, was potentially linked to onsite erosion, landslides, and sediment disturbance (Lin et al. 2011), which happened strongly during the rainy season in the study areas, compared to the dry season. The study area had a high rainfall, concentrated during the rainy season from September to December. Moreover, the topography of the study region featured steep slopes and numerous mountains, which enhanced the likelihood of onsite erosion or landslides, especially during periods of heavy rainfall. Additionally, the vigorous water flow during the rainy season had the potential to disturb sediment at the bottom of water bodies, leading to its redistribution into the upper water layer and causing pollution (Lin et al. 2011). The common source for turbidity and TSS in the

surface water systems in the current study was also confirmed by the observations that both parameters exhibited statistically higher values during the rainy season compared to the dry season (Fig. 4) and that they were significantly correlated with each other (Supplementary Table 1). Two other parameters, temperature, and pH exhibiting elevated loading values with factor 4 (Table 2), may be influenced by climatic factors, particularly air temperature. High air temperature during the dry season increased the temperature of surface water, compared to low water temperature in the rainy season (Fig. 5). Conversely, water pH is primarily associated with hydrogen ions ( $H^+$ ) in the water. High temperatures during the dry season may reduce pH due to increased dissociation of  $H^+$  from water molecules or greater accumulation of carbon dioxide (Oh et al. 2009; Riedel 2019). Nevertheless, temperature and water pH do not show a significant correlation, necessitating further studies to clarify.

## 4.2 The overall effects of seasons

Seasonal variations are closely linked to hydraulic parameters such as flow rate, velocity, and water depth, which in turn influence the quality of the surface water system. Our study revealed that the impacts of seasonal variation on WQI differed among three water bodies with varying hydraulic parameters. While lakes and rivers showed statistically similar WQI between the two seasons, canals exhibited substantially lower WQI in the dry season than in the rainy season (Fig. 1). This key finding can be attributed to the strong relationship between surface water quality parameters and hydraulic geometry factors, including bankfull width, depth, velocity, and discharge (Jung et al. 2013; Obateru et al. 2023). It is generally accepted that increased rainfall during the wet season leads to higher velocity, flow rate, and total discharge in local water bodies compared to the dry season. In canals, due to their narrow width, the greater flow rate and velocity during the rainy season may result in rapid transport of pollutants to lakes and rivers, while in the dry season, the lower flow rates and velocities allow pollutants to reside longer in the canals. Additionally, evaporation during the dry season contributes to an increased concentration of pollutants (Faulstich et al. 2023). These factors collectively contribute to lower pollutant concentrations in canals during the rainy season, resulting in a higher WQI compared to the dry season.

In rivers and lakes, key parameters such as  $NH_4^+$ ,  $NO_3^-$ ,  $NO_2^-$ ,  $PO_4^{3-}$ , COD, and  $BOD_5$  exhibited higher levels during the rainy season than during the dry season (Figs. 2 and 3). The heightened water originating from pollution sources during the rainy season carries a greater load of pollutants into larger water bodies such as rivers and lakes through

narrow water bodies such as canals. This phenomenon may account for the observed trend of elevated levels of these parameters in lakes and rivers during the rainy season compared to the dry season. The findings indicate the important role of rainwater in washing away and transporting pollutants from their sources to rivers and lakes (Yang et al. 2021). Meanwhile, in canals, except  $NO_2^-$ , these parameters were higher in the dry season than in the rainy season. Compared to rivers and lakes, canals are expected to have a shorter water residence time, determined by the ratio of water-storage capacity to flow rate (Rueda et al. 2006). This implies that pollutants in canals are likely to persist for a shorter duration compared to rivers and lakes.

The parameters,  $Cl^-$  (Fig. 3f), Coliform (Fig. 4d), and temperature (Fig. 5b) exhibited higher values during the dry season than the rainy season in all three water bodies of the surface water system. These findings can be attributable to the elevated temperature of the surface water system during the dry season, fostering improved microbial activities, including increased coliform bacteria. Notably, coliform bacteria thrive within an optimal temperature range from 35 to 37 °C (Li and Liu 2019), leading to their higher density during the dry season than the rainy season. The elevated concentration of  $Cl^-$  might be related to dilution effects during the dry season, resulting in higher levels during the high-temperature season. Moreover, the rainy season, generating substantial rainwater rapidly transports organic matter from canals to rivers and lakes. This process leads to lower  $BOD_5$  and COD levels in canals during the rainy season compared to the dry season (Fig. 3b and c), subsequently elevating the content of these two parameters in rivers and lakes. Furthermore, heightened rainfall contributes to increased turbidity and TSS across all three water bodies, primarily as a result of onsite erosion, landslides, and disruption of bottom sediment (Lin et al. 2011).

## 4.3 The interaction of seasonal variation and pollution sources in the surface water system

The impacts of seasonal variation on water quality depend not only on hydraulic parameters such as velocity, flow rate, and total discharge but also on pollution sources. These sources were identified as agricultural activities, residential areas, onsite erosion, landslides, sediment disturbance, and climatic factors. The exponential WQI1, indicative of agriculture-derived pollution sources, exhibited similarity in lakes and rivers across two seasons (Fig. 2). This suggests that pollution sources may not have a direct impact on water quality in these two water bodies. The great dilution effects and self-purification capacity of these relatively large and deep water bodies may enhance their WQI compared to canals (Farhadian et al. 2015; Liu and Li 2023). The

effects of seasonal variation and agriculture-derived pollution sources are more evident in canals, where WQI1 was statistically lower in the dry season than in the rainy season. Additionally, WQI1 also accounted for 93.2 to 94.96% of the total variance of WQI in canals (Table 3), highlighting the important role of this pollution source for canal water quality. Because the study region has two primary rice seasons, falling within the dry season (Le and Nguyen 2023), more pollutants derived from agricultural areas can be expected, accounting for this finding. This indicates that canals may receive more pollutants originating from agricultural fields, which are more intensively cultivated during the dry season in the study area. Upon collecting pollutants canals may transport them to larger water bodies such as rivers and lakes, where they can undergo self-assimilation, lowering their levels (Darji et al. 2022; Farhadian et al. 2015). This process explains the higher WQI1 observed in lakes and rivers than in canals.

The componential WQI2, reflecting pollution sources from residential areas, was statistically better in the rainy season than in the dry season (Fig. 3), which is in line with findings from Jia et al. (2021). Moreover, canals exhibited a considerably lower WQI2, compared to the other water bodies. These findings indicate that residential areas-originating pollution sources may directly lower WQI2, while the rainy season induces dilution effects to improve the water quality of the inland water resources in the current study. Onsite erosion, landslides, and sediment disruption constitute pollution sources, accounting for the exponential WQI3. This may explain a lower WQI3 in the rainy season than in the dry season. Rainstorms can trigger onsite landslides, erosion, or disruption of bottom sediment, leading to increased turbidity and TSS of the three water bodies.

#### 4.4 Overall water quality of the surface water system and implication for management

The overall WQI in the surface water system was significantly higher in lakes and rivers than in canals, in line with other studies (Le et al. 2023b). Canals, being direct conduits to pollution sources, receive a greater influx of pollutants from their origins and subsequently transport them to rivers and lakes. Consequently, water collected from canals tends to be more polluted than that from rivers and lakes. In contrast, larger water reservoirs of lakes and rivers may exhibit better self-purification processes and longer residence time (Tong et al. 2019), contributing to an overall improvement in water quality in the study region. Among the four primary pollution sources exerting the most significant impact on the surface water quality of rivers, lakes, and canals (Table 3), the first two - agricultural production and residential areas - are anthropogenic pollution sources. These sources play an

important role in determining nine biochemical parameters ( $\text{PO}_4^{3-}$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{NH}_4^+$ , COD, BOD<sub>5</sub>, DO, and coliforms), associated with factors 1 and 2. Meanwhile, the last two sources are natural pollution contributors, decisively influencing the remaining four physicochemical parameters (turbidity, TSS, temperature, and pH) corresponding to factors 3 and 4. Managing these pollution sources is essential for enhancing the water quality of the surface water system.

The current study reveals varying water quality in the surface water system, influenced by pollution sources, seasonal variation, and specific pollutants. The water quality in lakes and rivers is primarily shaped by pollution from residential areas and onsite erosion and landslides, while canals are driven by agricultural pollution sources (Table 3). Agricultural production, characterized by inorganic-nutrient contamination, represents a non-point pollution source directly discharged into canals before reaching rivers and lakes (O'Geen et al. 2010). Conversely, pollution originating from residential areas is characterized by organic matter, accounting for COD, BOD<sub>5</sub>, DO, and coliforms (Table 2). Lakes and rivers receive and accumulate organic pollutants that are also transferred from non-point sources. Factor 3 reflecting onsite landslides, erosion, or sediment disruption, is also important in determining water quality in lakes and rivers, typically during the rainy season. These findings highlight an important discovery, notably originating from the region with limited terrain, brief and steep rivers, and canals.

While water in canals is qualified for irrigation for agricultural or horticultural production, water in rivers and lakes with higher quality can be used for daily consumption by humans after appropriate treatments. In the long term, the three most important pollution sources should be managed for enhancing water quality and preserving the environment. Tailoring management strategies to suit the characteristics of each pollution source is crucial. This involves integrating a mix of targeted technical solutions, regulatory measures, public awareness initiatives, and infrastructure enhancements. By combining these strategies and customizing them based on specific regional and pollution source characteristics, it is possible to improve the quality of the surface water systems in various regions worldwide, preserving water quality for sustainable development.

## 5 Conclusions

The current study reveals that the quality of the surface water system is influenced by four primary pollution sources derived from agricultural activities, residential areas, onsite erosion and landslides, sediment disruption, and climate-related factors. The effects of these pollution sources vary

seasonally, with the dry season showing detrimental impacts on canals but no significant influence on lakes and rivers when compared to the rainy season. In the dry season, surface water quality in lakes and rivers is driven by pollution from residential areas, whereas pollution sources in the form of onsite erosion, landslides, and sediment disruption take precedence during the rainy season. Conversely, canals are primarily influenced by agriculture-based pollution sources throughout both seasons. Enhanced self-purification and longer water residence time in lakes and rivers could be the key mechanisms ameliorating the impacts of pollution sources and seasonal variations in these two water bodies, while dilution effects, rapid pollutant transport, and direct pollution input may be the reasons contributing to affecting water quality in canals. Overall, lakes and rivers exhibit higher water quality than canals, influenced by pollution sources and seasonal changes. In essence, the water quality in the surface water system, encompassing lakes, rivers, and canals, is predominantly shaped by four pollution sources that interact with seasonal variation. Effective management of these pollution sources is crucial for maintaining high water quality and ensuring a sustainable, healthy environment.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s00477-025-02948-8>.

**Acknowledgements** This research is supported by Industrial University of Ho Chi Minh City (IUH) under grant number 108/HD-DHCN. The authors extend their sincere gratitude to the Department of Natural Resources and Environment of Khanh Hoa province, the University of Industry of Ho Chi Minh City (IUH), and the dedicated efforts of the staff and students at the Institute of Science, Technology, and Environmental Management (IESEM-IUH) for their valuable support, assistance, and contributions to the successful completion of this research project.

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

**Funding** declaration.

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

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

**Ethical 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.

## References

- Anh NT, Can LD, Nhan NT, Schmalz B, Luu TL (2023) Influences of key factors on river water quality in urban and rural areas: A review. *Case Stud Chem Environ Eng* 8:100424. <https://doi.org/10.1016/j.cscee.2023.100424>
- Azha SF, Sidek LM, Ahmad Z, Zhang J, Basri H, Zawawi MH, Noh NM, Ahmed AN (2023) Enhancing river health monitoring: developing a reliable predictive model and mitigation plan. *Ecol Ind* 156:111190. <https://doi.org/10.1016/j.ecolind.2023.111190>
- Bănăduc D, Simić V, Cianfaglione K, Barinova S, Afanasyev S, Öktener A, McCall G, Simić S, Curtean-Bănăduc A (2022) Freshwater as a sustainable resource and generator of secondary resources in the 21st century: stressors, threats, risks, management and protection strategies, and conservation approaches. *Int J Environ Res Public Health* 19. <https://doi.org/10.3390/ijerph192416570>
- Berger M, Cauty SWJ, Tuholske C, Halpern BS (2022) Sources and discharge of nitrogen pollution from agriculture and wastewater in the Mesoamerican reef region. *Ocean Coastal Manage* 227:106269. <https://doi.org/10.1016/j.ocecoaman.2022.106269>
- Bhateria R, Jain D (2016) Water quality assessment of lake water: a review. *Sustainable Water Resour Manage* 2:161–173. <https://doi.org/10.1007/s40899-015-0014-7>
- Chidiac S, El Najjar P, Ouaini N, El Rayess Y, El Azzi D (2023) A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. *Rev Environ Sci Biotechnol* 22:349–395. <https://doi.org/10.1007/s11157-023-09650-7>
- 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. <https://doi.org/10.3390/su10010003>
- Darji J, Lodha P, Tyagi S (2022) Assimilative capacity and water quality modeling of rivers: a review. *AQUA - Water Infrastructure Ecosyst Soc* 71:1127–1147. <https://doi.org/10.2166/aqua.2022.063>
- Dauda AB, Ajadi A, Tola-Fabunmi AS, Akinwale AO (2019) Waste production in aquaculture: sources, components and managements in different culture systems. *Aquaculture Fisheries* 4:81–88. <https://doi.org/10.1016/j.aaf.2018.10.002>
- Dey S, Botta S, Kallam R, Angadala R, Andugala J (2021) Seasonal variation in water quality parameters of Gudlavalleru engineering college pond. *Curr Res Green Sustainable Chem* 4:100058. <https://doi.org/10.1016/j.crgsc.2021.100058>
- Donre (2020) Report on environmental status of Khanh Hoa Province in the period 2016–2020. Department of Natural Resources and Environment of Khanh Hoa province
- Farhadian M, Bozorg-Haddad O, Seifollahi-Aghmiuni S, Loaiciga H (2015) Assimilative capacity and flow Dilution for water quality protection in rivers. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000234](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000234). 19
- Faulstich L, Arendt R, Reinhardt-Imjela C, Schulte A, Lengricht J, Johannes P (2023) Water and sediment pollution of intensively used surface waters during a drought period — a case study in central Northern Namibia. *Environ Monit Assess* 195:924. <https://doi.org/10.1007/s10661-023-11505-1>
- Geilfus C-M (2019) Chloride in soil: from nutrient to soil pollutant. *Environ Exp Bot* 157:299–309. <https://doi.org/10.1016/j.envexpbot.2018.10.035>
- Giao NT, Ly NHT (2023) Evaluating surface water quality in a coastal Province of Vietnamese Mekong Delta using water quality index

- and statistical methods. *Pol J Environ Stud* 32:2113–2124. <https://doi.org/10.15244/pjoes/159897>
- Gomes PIA, Fernando BAVW, Dehini GK (2019) Assessment of pollution sources, fate of pollutants, and potential instream interventions to mitigate pollution of earthen canals of urban to rural-urban fringe. *Water Air Soil Pollut* 230:262. <https://doi.org/10.1007/s11270-019-4314-7>
- Hajrasuliha S, Cassel DK, Rezaiejad Y (1991) Estimation of chloride ion concentration in saline soils from measurement of electrical conductivity of saturated soil extracts. *Geoderma* 49:117–127. [https://doi.org/10.1016/0016-7061\(91\)90095-B](https://doi.org/10.1016/0016-7061(91)90095-B)
- Hong P, Wu X, Shu Y, Wang C, Tian C, Gong S, Cai P, Donde 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. <https://doi.org/10.1186/s13568-019-0855-9>
- Hu H, Li X, Wu S, Yang C (2020) Sustainable livestock wastewater treatment via phytoremediation: current status and future perspectives. *Bioresour Technol* 315:123809. <https://doi.org/10.1016/j.biortech.2020.123809>
- Islam AKMK (2023) Domestic and industrial wastewater generation and its energy recovery potential in Bangladesh. *Clean Energy Syst* 6:100092. <https://doi.org/10.1016/j.cles.2023.100092>
- Jia Z, Chang X, Duan T, Wang X, Wei T, Li Y (2021) Water quality responses to rainfall and surrounding land uses in urban lakes. *J Environ Manage* 298:113514. <https://doi.org/10.1016/j.jenvman.2021.113514>
- Jiao Y (2021) Chap. 2 - Waste to biohydrogen: potential and feasibility. In: Zhang Q, He C, Ren J, Goodsite M (eds) *Waste to renewable biohydrogen*. Academic, pp 33–53. <https://doi.org/10.1016/B978-0-12-821659-0.00006-X>
- Jung D, Paik K, Kim JH (2013) Relationship between downstream hydraulic geometry and suspended sediment concentration characteristics. *J Hydro-Environ Res* 7:243–252. <https://doi.org/10.1016/j.jher.2013.03.002>
- Khanh Hoa statistics offices (2020) *Statistical yearbook of Khanh Hoa 2020*. Ho Chi Minh City General Publishing House, Ho Chi Minh City
- Kuriata-Potasznik A, Szymczyk S, Skwierawski A (2020) Influence of cascading river–lake systems on the dynamics of nutrient circulation in catchment areas. *Water* 12:1144
- Le TV, Nguyen BT (2023) Heavy metal pollution in surface water bodies in provincial Khanh Hoa, Vietnam: pollution and human health risk assessment, source quantification, and implications for sustainable management and development. *Environ Pollut* 123216. <https://doi.org/10.1016/j.envpol.2023.123216>
- Le TV, Do DD, Nguyen BT (2023a) Spatiotemporal assessment and pollution-source identification and quantification of the surface water system in a coastal region of Vietnam. *Hydrol Sci J* 1–12. <https://doi.org/10.1080/02626667.2023.2192352>
- Le TV, Nguyen DTP, Nguyen BT (2023b) Spatial and Temporal analysis and quantification of pollution sources of the surface water quality in a coastal Province in Vietnam. *Environ Monit Assess* 195:408. <https://doi.org/10.1007/s10661-023-11026-x>
- Li D, Liu S (2019) Chap. 12 - water quality monitoring in aquaculture. In: Li D, Liu S (eds) *Water quality monitoring and management*. Academic, pp 303–328. <https://doi.org/10.1016/B978-0-12-811330-1.00012-0>
- Lin G-W, Chen H, Petley D, Horng M-J, Wu S-J, Chuang B (2011) Impact of rainstorm-triggered landslides on high turbidity in a mountain reservoir. *Eng Geol - ENG GEOL* 117:97–103. <https://doi.org/10.1016/j.enggeo.2010.10.009>
- Liu Y, Li L (2023) Multiple evaluations of the Spatial and Temporal characteristics of surface water quality in the typical area of the Yangtze river Delta of China using the water quality index and multivariate statistical analysis: A case study in Shengzhou City. *Int J Environ Res Public Health* 20:2883
- Liu L, Zheng X, Wei X, Kai Z, Xu Y (2021) Excessive application of chemical fertilizer and organophosphorus pesticides induced total phosphorus loss from planting causing surface water eutrophication. *Sci Rep* 11:23015. <https://doi.org/10.1038/s41598-021-02521-7>
- Ly N, Giao N (2018) Surface water quality in canals in an Giang Province, Viet Nam, from 2009 to 2016. *J Vietnamese Environ* 10:113–119. <https://doi.org/10.13141/jve.vol10.no2.pp113-119>
- Ma X, Li N, Yang H, Li Y (2022) Exploring the relationship between urbanization and water environment based on coupling analysis in Nanjing, East China. *Environ Sci Pollut Res Int* 29:4654–4667. <https://doi.org/10.1007/s11356-021-15161-1>
- Monre (2015) *National technical regulation on surface water quality QCVN 08-MT:2015/BTNMT*. Ministry of Natural Resources and Environment
- Müller A, Österlund H, Marsalek J, Viklander M (2020) The pollution conveyed by urban runoff: A review of sources. *Sci Total Environ* 709:136125. <https://doi.org/10.1016/j.scitotenv.2019.136125>
- Némethy SA, Ternell A, Borrmalm L, Lagerqvist B, Szemethy L (2022) Environmental viability analysis of connected European inland–marine waterways and their services in view of climate change. *Atmos* 13:951
- Nguyen TTN, Némery J, Gratiot N, Strady E, Tran VQ, Nguyen AT, Aimé J, Peyne A (2019) Nutrient dynamics and eutrophication assessment in the tropical river system of Saigon – Dongnai (southern Vietnam). *Sci Total Environ* 653:370–383. <https://doi.org/10.1016/j.scitotenv.2018.10.319>
- Nguyen TB, Vo LD, Nguyen TX, Quang NX (2020) The interactive effects of natural factor and pollution source on surface water quality in the lower Mekong river basin, Southwestern Vietnam. *Water Resour* 47:865–876. <https://doi.org/10.1134/S0097807820050024>
- 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. *Environ Monit Assess* 193. <https://doi.org/10.1007/s10661-021-09015-z>
- O’Geen AT, Budd R, Gan J, Maynard JJ, Parikh SJ, Dahlgren RA (2010) Chapter One - Mitigating nonpoint source pollution in agriculture with constructed and restored wetlands. In: Sparks DL (ed) *Advances in agronomy*. Academic, pp 1–76. [https://doi.org/10.1016/S0065-2113\(10\)08001-6](https://doi.org/10.1016/S0065-2113(10)08001-6)
- Obateru RO, Fashae OA, Osakunih OI, Olusola AO (2023) Hydraulic geometry influences some water quality parameters in a tropical headwater basin in Southwestern Nigeria. *Acta Geophys* 71:1857–1866. <https://doi.org/10.1007/s11600-022-00958-6>
- Oh H-C, Seo H-I, Kim Y-C (2009) Dissociation of H<sub>2</sub>O molecule adsorbed on Si (001) 2×1 surface: a theoretical study. *MRS Online Proceedings Library* 1145:435. <https://doi.org/10.1557/PROC-1145-MM04-35>
- Pati SS, Nayak S, Mishra S, Panda BS, Mahala SS, Mohanty SK, Behera R, Mallick N, Murugesan K (2023) A comprehensive study of the estuary sea environment in the Bay of Bengal, near the Mahanadi river confluence. *Discover Water* 3:20. <https://doi.org/10.1007/s43832-023-00044-y>
- Putri MSA, 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
- Qadir A, Malik RN, Husain SZ (2008) Spatio-temporal variations in water quality of nullah Aik-tributary of the river Chenab. *Pakistan Environ Monit Assess* 140:43–59. <https://doi.org/10.1007/s10661-007-9846-4>
- Rashmi I, Roy T, K KS, Pal R, Coumar V, Kala S, K.C S (2020) Organic and inorganic fertilizer contaminants in agriculture:

- Impact on soil and water resources. In, pp. 3–41. [https://doi.org/10.1007/978-3-030-41552-5\\_1](https://doi.org/10.1007/978-3-030-41552-5_1)
- Reda M (2019) Characterization of surface water quality along Ismailia canal, Nile river, Egypt. *J Adv Civil Environ Eng* 2:01. <https://doi.org/10.30659/jacee.2.1.01-14>
- Riedel T (2019) Temperature-associated changes in groundwater quality. *J Hyd* 572:206–212. <https://doi.org/10.1016/j.jhydrol.2019.02.059>
- Ringler C, Agbonlahor M, Barron J, Baye K, Meenakshi JV, Mekonnen DK, Uhlenbrook S (2022) The role of water in transforming food systems. *Global Food Secur* 33:100639. <https://doi.org/10.1016/j.gfs.2022.100639>
- Romano N, Zeng C (2013) Toxic effects of ammonia, nitrite, and nitrate to decapod crustaceans: A review on factors influencing their toxicity, physiological consequences, and coping mechanisms. *Rev Fish Sci* 21(2013). <https://doi.org/10.1080/10641262.2012.753404>
- Rueda F, Moreno-Ostos E, Armengol J (2006) The residence time of river water in reservoirs. *Ecol Model* 191:260–274. <https://doi.org/10.1016/j.ecolmodel.2005.04.030>
- Tong Y, Li J, Qi M, Zhang X, Wang M, Liu X, Zhang W, Wang X, Lu Y, Lin Y (2019) Impacts of water residence time on nitrogen budget of lakes and reservoirs. *Sci Total Environ* 646:75–83. <https://doi.org/10.1016/j.scitotenv.2018.07.255>
- Vadde KK, Wang J, Cao L, Yuan T, McCarthy AJ, Sekar R (2018) Assessment of water quality and identification of pollution risk locations in Tiaoxi river (Taihu Watershed), China. *Water* 10:183
- Wang S, Nie X, Ran F, Liao W, Yang C, Xiao T, Liu Y, Liu Y, Li Z (2023) Human activities control the source of eroded organic carbon in lake sediments over the last 100 years: evidence from stable isotope fingerprinting. *Fundamental Res*. <https://doi.org/10.1016/j.fmre.2023.04.015>
- Woldeab B, Beyene A, Ambelu A, Buffam I, Mereta ST (2018) Seasonal and Spatial variation of reservoir water quality in the Southwest of Ethiopia. *Environ Monit Assess* 190:163. <https://doi.org/10.1007/s10661-018-6527-4>
- 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. *Environ Science: Processes Impacts* 20:863–891. <https://doi.org/10.1039/C8EM00042E>
- Xia Y, Zhang M, Tsang DCW, Geng N, Lu D, Zhu L, Igalavithana AD, Dissanayake PD, Rinklebe J, Yang X, Ok YS (2020) Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. *Appl Biol Chem* 63:8. <https://doi.org/10.1186/s13765-020-0493-6>
- Yang L, Li J, Zhou K, Feng P, Dong L (2021) The effects of surface pollution on urban river water quality under rainfall events in Wuqing district, Tianjin, China. *J Clean Prod* 293:126136. <https://doi.org/10.1016/j.jclepro.2021.126136>
- Zhang J, Zhou J, Chen Y, Wei X, Zeng Y, Sun Y (2023) Identifying the factors controlling surface water and groundwater chemical characteristics and irrigation suitability in the Yarkant river basin, Northwest China. *Environ Res* 223:115452. <https://doi.org/10.1016/j.envres.2023.115452>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.