Combination of water quality, pollution indices, and multivariate statistical techniques for evaluating the surface water quality variation in Can Tho city, Vietnam

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Abstract This study assessed the surface water quality in Can Tho city, Vietnam, using a combination of water quality, pollution indices, and multivariate statistical methods. Surface water samples were collected at 38 locations with a frequency of 4 times in 2020 (March, June, September, and December) and at the time of high and low tides to analyze for 18 indicators. Results showed that surface water in Can Tho city was contaminated with organic matters and microorganisms. Parameters of pH, turbidity, total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), $N-NH_4^+$, and $N-NO_3^-$ are significantly increased with low tide. Comprehensive pollution index indicated mild to moderately polluted water in March, June, and September and moderately to severely polluted water in December. Organic pollution index revealed that surface water quality in all locations was polluted with organic matters during the study period especially in March and December. The water quality index also indicated that water quality in December was mostly classified as moderate and bad. The principal component analysis indicated that surface water quality could be affected by five main sources that explain 64.40% of the total variation. This significantly caused the fluctuation of pH, temperature, turbidity, TSS, DO, BOD, COD, $N-NH_4^+$, $P-PO_4^{3-}$, Fe, and As, which should all be the focus for future monitoring. Surface water management in Can Tho city should also emphasize on the wastewater from urbanization and agriculture, which has been recognized by the analysis to have highest contribution to organic, nutrient, and microbial pollutants in the water bodies.

Keywords Can Tho city · Surface water quality · Water pollution · Water quality index · Comprehensive pollution index

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Introduction

Can Tho city, located in the center of the Mekong Delta, plays an important role in the economic development and economic restructuring towards industrialization and modernization of the region (Can Tho's People Committee, 2020). The city's gross regional domestic product in 2020 was estimated to increase by 1.02% compared to 2019. Of this number, the agriculture, forestry, and fishery sector were expected to increase by 1.58%, while the industry and construction sector and the service sector were expected to grow by 1.69% and 0.51%,

respectively. Due to this economic acceleration, the water demand for production processes was increasingly required, thereby generating more wastewater (Can Tho's People Committee, 2020). Although the wastewater and solid waste treatment systems in the Mekong Delta have been improved in terms of technology, they were still ineffective. As a result of this deficiency, water pollution has arisen in this area (Ojok et al., 2017; Ministry of Natural Resources and Environment (MONRE), 2018; Atwebembeire et al., 2019).

Water quality monitoring can reflect the effectiveness of the regulations or legal documents on water quality protection. For example, the Vietnamese Law on Environmental Protection stipulates water quality monitoring as an important and regular task for central and local authorities (Vietnam National Assembly, 2020). This task is divided into background or baseline monitoring, impact monitoring, and flux monitoring, for which the monitoring sites are usually located in wetlands and border areas (baseline monitoring), in the areas where there are high waste generation sources such as urban areas (impact monitoring), and in estuaries (flux monitoring) (Vietnam National Assembly, 2020). The indicators used in the monitoring program can reflect the characteristics of wastewater from socio-economic development processes, thereby suggesting solutions in the waste management process (MONRE, 2015). The monitoring indicators can include physical parameters (such as temperature, turbidity, TSS, and dissolved oxygen), chemical parameters (such as BOD, COD, $N–NH_4^+$, $N–NO_2^-$, $N–NO_3^-$, $P–PO_4^{3-}$, total nitrogen, and total phosphorus), biological factors (such as phytoplankton, zooplankton, benthic, *Escherichia coli*, and coliform bacteria), heavy metals (such as Fe, Cr, As, Pb, and Hg), and pesticide compounds (such as organophosphate and carbamate) (Kazi et al., 2009; Oketola et al., 2013; MONRE, 2015; Islam et al., 2017; Chounlamany et al., 2017; Zoltan et al., 2021).

In Vietnam, surface water quality is assessed through the water quality index (WQI) and Vietnamese standards (MONRE, 2015; Vietnam Environment Administration (VEA), 2019; Giao et al., 2021a, 2021c). However, considering each parameter separately one by one for the analysis of water quality may not cover all aspects of the water quality assessment or not able to obtain important information from the related parameters (Chounlamany et al., 2017; Giao et al., 2021c; Kazi et al., 2009; Oketola et al., 2013; Zoltan et al., 2021). Therefore, various

methods can be used to supplement the water quality assessment by WQI such as the comprehensive pollution index (CPI) and the organic pollution index (OPI) (Qin et al., 2020; Son et al., 2020; Zhang et al., 2020). Using the WQI, Giao et al. (2021c) found that the surface water in Dong Thap province was classified as poor quality, of which further results from CPI and OPI showed the high potential of eutrophication in Cau River (Son et al., 2020). Multivariate statistical methods, including cluster analysis (CA), principal component analysis (PCA) combined with APCS-MLR model, and numerical discriminant analysis, can also be used for clustering monitoring location, identifying potential pollution sources and the extent of their contribution to the fluctuations, and differentiating the water quality indicators by time and study space, respectively (Kazi et al., 2009; Oketola et al., 2013; MONRE, 2015; Islam et al., 2017; Chounlamany et al., 2017; Zhang et al., 2020; Qin, et al., 2020; Zoltan et al., 2021; Giao et al., 2021a). These methods allow all the analytical criteria to be collectively considered in the water quality assessment, providing more advantages over the current assessment method in Vietnam (Giao et al., 2021a).

There have been studies on surface water quality of Vietnam that applied statistical analysis methods to explain the effect of important parameters on surface water quality. Prathumratana et al. (2008) used Pearson correlation to analyze the water quality, climatic data, and hydrological parameters in the lower Mekong River areas and found the strong correlation between the water quality and climatic data. Pearson correlation and principal correspondence and analyses were also used to separate the groups of water quality and plankton community structure along the Day River in Red River delta, northern Vietnam (Hoang et al., 2018). It has been shown by another study that that the surface water quality in the northern part of Vietnam was influenced by anthropogenic sources during rainy and dry seasons in the Day River and Nhue River according to Mann–Whitney U test and hierarchical cluster analysis (Hanh et al., 2010). Son et al. (2020) used pollution indices including WQI, CPI, and OPI to assess the river water quality of Cau River in the north of Vietnam. The water quality indices showed variations depending on location and season, and the analysis by CA method could categorize the water monitoring points into five groups with the gradual quality deterioration. CA and PCA methods

have also been proved useful for grouping and determining the important parameters in surface water quality analysis by our previous studies in the Mekong Delta region including Hau Giang province (Giao, 2020a, b), Tien Giang province (Giao et al., 2021a), Dong Thap province (Giao et al., 2021b, c), and An Giang province (Giao, 2020a; Hong & Giao, 2022).

Despite the importance of Can Tho city, only few studies have evaluated the surface water quality using the statistical analysis. According to the 2008–2012 data from 38 sampling sites, Phung et al. (2015) applied multivariate statistical techniques including CA and PCA to group the sites into three clusters: mixed urban–rural areas, agricultural areas, and industrial zone. Wilbers et al. (2014) also monitored the surface water pollution during 2011–2012 in Can Tho city, Hau Giang, and Soc Trang provinces. The study could identify the key factors explaining the observed pollution in the surface water through PCA and the significant differences in water quality from season and tidal movement. Based on these previous studies, it is important to have more recent and comprehensive studies that can determine and explain the recent changes of the surface water in Can Tho city. Therefore, the objective of this study is to analyze the fluctuations in the surface water quality of Can Tho city by using the integration of the three water quality and pollution indices (WQI, CPI, and OPI) and PCA with the support of APCS-MLR model. The tidal and seasonal effects on surface water quality were observed along with the key variables and pollution source contribution to the surface water quality. The findings from this study not only serve as a model of a complete monitoring task but also provide important reference values in analyzing and evaluating changes in surface water quality in Can Tho city, Vietnam.

Materials and methods

Description of the study area

Can Tho city is situated between longitudes 105°13′38″–105°50′35″E and latitudes 09°55′08″–10°19′38″N. The total area is 1408.949 km², accounting for 3.5% of the total area of the Mekong Delta. Can Tho borders An Giang province in the north, Dong Thap and Vinh Long provinces in the east, Kien Giang province in the west, and Hau Giang province in the south. The administrative unit of the city consists of 9 districts (Ninh Kieu, O Mon, Binh Thuy, Cai Rang, Thot Not, Vinh Thanh, Co Do, Thoi Lai, Phong Dien), 44 wards, 5 towns, and 36 communes (Can Tho's People Committee, 2020). In 2019, Can Tho had a total population of 1.235 million people, with a population density of 859 people/km² (Can Tho's People Commitee, 2020).

Can Tho has a flat topography with the slope from the northeast lower to the southwest and from the Hau River lower to the inland field. This is a land with an interlaced system of more than 158 rivers and canals, with an elevation ranging from 0.8 to 1.0 m above sea level at Hon Dau national landmark. The density of rivers and canals is relatively large, about 1.8 up to over 2 km/km², along the Hau River in Ninh Kieu, O Mon, Cai Rang, and Thot Not districts (Can Tho's People Committee, 2020). The hydrological regime of the river and canal system is governed by the flow of the Mekong River through the Hau River, the tides of the East Sea, regional rainfall, and infrastructure systems (Mekong River Commission (MRC), 2015; (MONRE), 2015). Hau River is the western branch of the Mekong River in the territory of Vietnam, serving as the main source of freshwater supply for the Mekong Delta and Can Tho city, with a total length of 55 km flowing through Can Tho city and the average water flow of 5470–10,600 m³/s (flooding season) and 630–1840 m³/s (dry season) in 2020 (Can Tho Hydrological Station, 2020). The canal system includes the 16-km-long Can Tho canal, Binh Thuy canal, Tra Noc canal, O Mon canal, Thot Not canal, Cai San canal, and many other canals in the suburban districts (Can Tho's People Committee, 2020). These large canals channel water from Hau River into the inland areas and other canals of the neighboring provinces. This is a freshwater source all year round for irrigation in the dry season, for drainage effect in the flood season, and especially for traffic.

Sample collection and analysis of water quality

The monitoring data were collected in 2020 from the Department of Natural Resources and Environment of Can Tho city. Surface water samples were investigated at 38 locations (S1-S38) along all rivers and canals of Can Tho city (Fig. 1), with a frequency of 4

times per year (March, June, September, and December). These samples were also collected at the time of high tide and low tide for each monitoring period. After that, the samples were analyzed for 18 parameters, including pH, temperature, turbidity, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammonium ($N–NH_4^+$), nitrite ($N–NO_2^-$), nitrate ($N–NO_3^-$), orthophosphate ($P–PO_4^{3-}$), iron (Fe), fluoride (F^-), chromium (Cr), arsenic (As), lead (Pb), mercury (Hg), and total coliform. The temperature, pH, DO, and turbidity were measured in the field while other parameters were analyzed in the laboratory using standard methods (APHA, 2012). The

analytical methods for all parameters are presented in Table 1.

Data analysis

The characteristics of the surface water bodies of Can Tho city were evaluated using the national technical regulations on surface water quality (QCVN 08-MT:2015/BTNMT, column A1). Details of the allowable limits of each indicator are given in Table 1. In addition, the difference between low tide and high tide data in each sampling month was determined by the independent t-test analysis using the SPSS software (version 20.0, IBM Corp., Armonk, NY, USA).
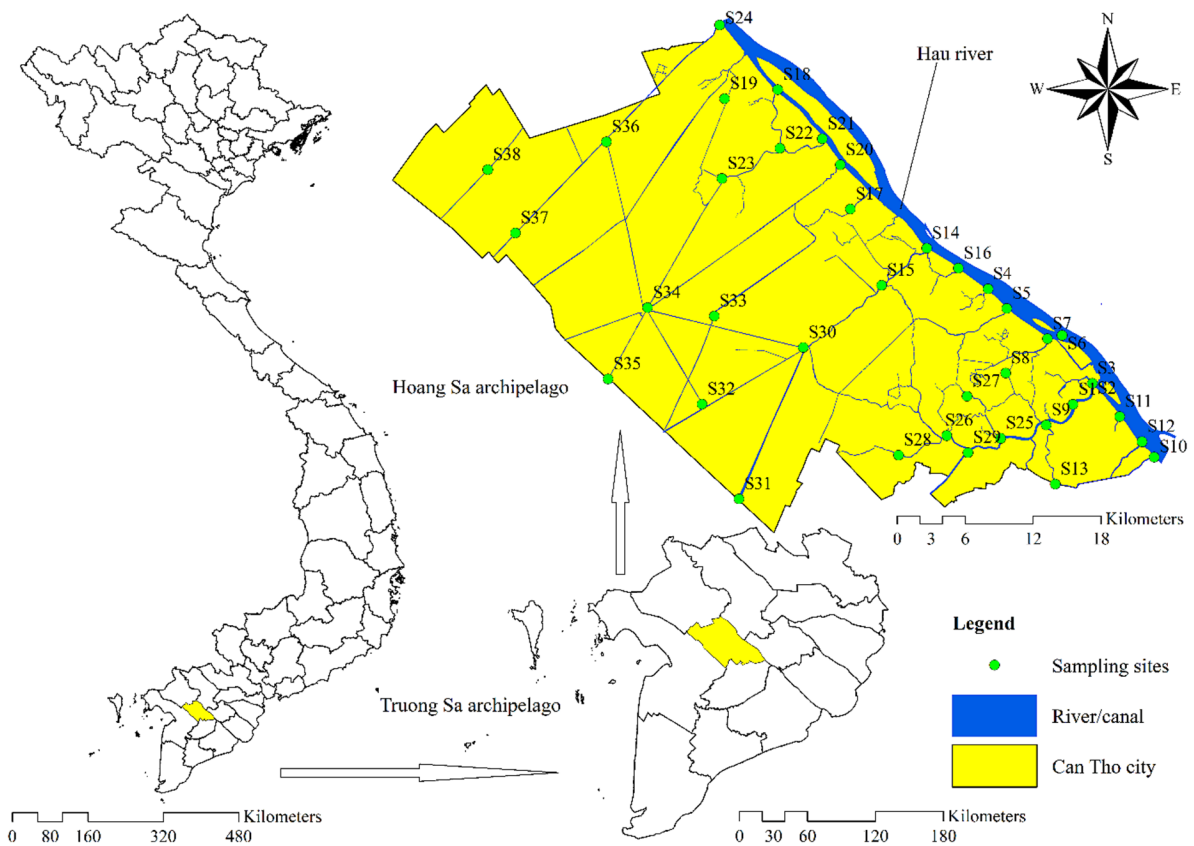

Fig. 1 Surface water sampling locations in Can Tho city

Table 1 Analytical methods and limit values for water bodies in Vietnam

Parameter	Description	Unit	Analytical methods	QCVN, A1
pH	pH	–	TCVN 6492:2011	6–8.5
Temp	Temperature	°C	SMEWW 2550B:2012	–
Turb	Turbidity	NTU	Turbidity meter	–
DO	Dissolved oxygen	mg/L	TCVN 7325:2004	≥ 6
BOD	Biochemical oxygen demand	mg/L	TCVN 6001–1:2008	4
COD	Chemical oxygen demand	mg/L	TCVN 6491:1999	10
TSS	Total suspended solids	mg/L	TCVN 6625:2000	20
$N\text{-}NH_4^+$	Ammonium	mg/L	TCVN 6179:1996	0.3
Fe	Total iron	mg/L	TCVN 6177:1996	0.5
$N\text{-}NO_2^-$	Nitrite	mg/L	SMEWW 4500-NO_2^-.B:2012	0.05
$N\text{-}NO_3^-$	Nitrate	mg/L	TCVN 6180:1996	2
$P\text{-}PO_4^{3-}$	Orthophosphate	mg/L	SMEWW 4500-PO_4^{3-}.E:2012	0.1
Cr	Chromium	mg/L	SMEWW 3500-Cr D	0.01
F^-	Flouride	Mg/L	SMEWW 4500-F^-.B&D:2012	1
As	Arsenic	mg/L	TCVN 6626:2000	0.01
Pb	Lead	mg/L	SMEWW 3113B:2017	0.02
Hg	Mercury	mg/L	TCVN 7877:2008	0.001
Coliform	Total coliform	MPN/100 mL	TCVN 6187–2:1996	2500

Water quality and pollution indices

The overall water quality was assessed using the CPI, OPI, and WQI. The CPI is calculated using Eq. (1):

$$CPI = \frac{1}{n} \sum_{i=1}^{n} PI_i \tag{1}$$

where $PI_i = \frac{C_i}{S_i}$, *n* is the number of parameters, C_i is the observed concentration of pollutants, and S_i is the limit value of the pollutant in QCVN 08-MT:2015/BTNMT.

The OPI is calculated using Eq. (2):

$$OPI = \frac{COD}{COD_s} + \frac{DIN}{DIN_s} + \frac{DIP}{DIP_s} - \frac{DO}{DO_s} \tag{2}$$

where COD, DIN ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $N\text{-}NO_2^-$,), DIP ($P\text{-}PO_4^{3-}$), and DO are the observed values in this study; CODs, DINs, DIPs, and DOs are the limit values in surface water in Vietnam.

According to theguidelines of the Vietnam Environment Administration (2019), two forms ofcalculation were introduced to calculate the WQI as described below.If the water body shows organic-pollution problems (OPI>1), the WQI will be calculated by Eq. (3). In contrast, the WQIwill be calculated based on Eq. (4).

$$WQI = \frac{WQI_{pH}}{100} \times \frac{(\prod_{i=1}^{4} WQI_1)^{\frac{1}{4}}}{100} \times \left[\left(\frac{1}{7} \sum_{i=1}^{7} WQI_{II} \right)^2 \times WQI_{coliform} \right]^{\frac{1}{3}} \tag{3}$$

$$WQI = \frac{WQI_{pH}}{100} \times \frac{(\prod_{i=1}^{4} WQI_1)^{\frac{1}{4}}}{100} \times \left[\left(\frac{1}{7} \sum_{i=1}^{7} WQI_{II} \right) \times WQI_{coliform} \right]^{\frac{1}{2}} \tag{4}$$

Identification of key parameters and sources affecting the water quality

PCA was employed to identify the source of contamination and was represented by principal components (PCs). Eigenvalues and weighting coefficients were used to evaluate the importance of the main components and the contribution of each parameter in each main component. The absolute value of the significant correlation coefficient is considered weak, moderate, and strong when its values are 0.3-0.5, 0.5-0.75, and > 0.75, respectively (Chounlamany et al., 2017; Islam et al., 2017). After identifying the sources from PCA, APCS-MLR model was applied to quantify further the contribution of latent factors (Qin et al., 2020; Su et al., 2011; Zhang et al., 2020). The contribution of pollution sources in the APCS-MLR method is calculated using Eq. (5):

$$C_i = (r_0)_i + \sum_{k=1}^{n} r_{ik} \times APCS_{jk} \quad (5)$$

where $(r_0)_i$ is the regression constant, r_{ik} is the regression coefficient of the source k (PC) for pollutant i, $APCS_{jk}$ is the absolute principal component score, and $r_{ik} \times APCS_{jk}$ is the average contribution of sources to parameter i.

The $APCS_{jk}$ value is calculated using the following Eqs. (6), (7) and (8):

(1) Normalization of pollutant content i is calculated by Eq. (6).

$$\left(Z_0\right)_i = \frac{0 - \overline{C_i}}{\sigma_i} \quad (6)$$

(2) The value assumed for the sample with zero pollutant concentration is calculated by Eq. (7).

$$(A_0)_k = \sum_{i=1}^{i} S_{ik} \times (Z_0)_i \quad (7)$$

(3) Calculation of APCS score of each source in the water sample at position j is calculated by Eq. (8).

$$APCS_{jk} = \left(A_z\right)_{jk} - \left(A_0\right)_k \quad (8)$$

From Eqs. (6), (7) and (8) $\overline{C}_i$ and σ_i are the mean and standard deviation of the observed parameters,

Table 2 The water quality classification value of the indices

Water quality index	Value	Classification
CPI[a]	0–0.2	Excellent quality
	0.21–0.4	Good
	0.41–1	Lightly polluted
	1.01–2	Moderately polluted
	> 2.01	Heavily polluted
OPI[a, b]	< 0	Excellent
	0–1	Good
	1–4	Polluted
	> 4	Extremely polluted
WQI[c]	91–100	Excellent
	76–90	Good
	51–75	Moderate
	26–50	Poor
	10–25	Very poor
	< 10	Heavily polluted

[a]Anh et al. (2020)
[b]Son et al. (2020)
[c]VEA (2019)

S_{ik} is the coefficient of the principal component points (loading), and $(A_z)_{jk}$ is the composite score of the main components (principal component score).

Negative values during the calculation were converted to positive contributions by taking the absolute value to avoid skewing the results of the contributions of the sources (Zhang et al., 2020). Classification of water quality according to CPI, OPI, and WQI is presented in Table 2.

Results and discussion

Tidal effect on surface water quality

The impact of tides on the surface water quality of Can Tho city is presented in Table 3. The pH of water bodies was ranging between 7.09 ± 0.24 and 7.83 ± 0.37, which was within the allowable limit of QCVN 08-MT:2015/BTNMT, column A1 (6.0–8.5). The pH during high tide tended to be significantly higher than that during low tide as observed from March to September ($p < 0.05$). Tides also influenced the water temperature from June to December. The temperature was ranging from 26.79 ± 0.32 to

Table 3 Characteristics of surface water quality in Can Tho city in 2020

Month	March		Sig	June		Sig	September		Sig	December		Sig
Tide	Low	High		Low	High		Low	High		Low	High	
pH	7.43±0.32	7.83±0.37	**0.00***	7.09±0.24	7.20±0.18	**0.03***	7.20±0.11	7.25±0.10	**0.03***	7.21±0.27	7.20±0.17	0.82
Temp	30.21±0.20	30.23±0.17	0.58	27.88±0.31	28.10±0.33	**0.00***	27.02±0.22	27.18±0.11	**0.00***	27.37±0.24	26.79±0.32	**0.00***
Turb	24.12±8.61	20.31±7.32	**0.04***	18.05±3.54	13.95±3.68	**0.00***	19.66±3.64	12.11±2.94	**0.00***	29.61±6.49	20.47±5.12	**0.00***
DO	5.76±0.38	5.56±0.30	**0.01***	5.68±0.24	5.38±0.21	**0.00***	6.05±0.26	5.59±0.34	**0.00***	5.97±0.27	5.72±0.34	**0.00***
BOD	8.21±1.60	6.82±1.98	**0.00***	6.76±1.57	5.08±1.10	**0.00***	6.13±1.40	5.29±1.33	**0.00***	8.32±1.96	5.29±1.37	**0.00***
COD	14.62±2.63	12.01±3.19	**0.00***	14.54±2.22	11.83±2.40	**0.00***	13.07±2.80	11.39±2.43	**0.00***	16.11±2.88	11.68±2.89	**0.00***
TSS	29.78±4.98	20.39±4.83	**0.00***	31.30±5.42	27.78±7.00	**0.02***	38.32±5.35	34.78±6.04	**0.01***	61.93±13.55	44.42±10.57	**0.00***
$N-NH_4^-$	0.25±0.06	0.20±0.07	**0.01***	0.19±0.04	0.16±0.04	**0.00***	0.12±0.03	0.08±0.03	**0.00***	0.23±0.06	0.17±0.06	**0.00***
$N-NO_2^-$	0.04±0.04	0.02±0.01	0.49	0.02±0.01	0.02±0.01	0.28	0.02±0.01	0.02±0.03	0.27	0.02±0.01	0.01±0.01	**0.01***
$N-NO_3^-$	0.95±0.27	0.72±0.26	**0.00***	0.78±0.30	0.51±0.28	**0.00***	0.52±0.25	0.76±0.33	**0.00***	1.08±0.34	0.33±0.13	**0.00***
$P-PO_{43}^-$	0.06±0.03	0.06±0.02	0.85	0.07±0.03	0.05±0.03	0.85	0.05±0.02	0.05±0.02	0.37	0.07±0.02	0.06±0.08	0.55
Fe	0.09±0.04	0.10±0.05	0.27	0.16±0.05	0.16±0.07	0.86	0.21±0.05	0.15±0.04	**0.00***	0.28±0.10	0.24±0.12	0.11
F^-	0.06±0.06	0.06±0.06	0.53	0.25±0.15	0.17±0.11	0.24	0.27±0.18	0.10±0.09	0.24	0.23±0.14	0.17±0.16	**0.02***
Cr	BDL	BDL	–	BDL	BDL	–	BDL	BDL	–	0.003±0.003	0.003±0.004	0.62
As	0.002±0.000	0.002±0.000	0.64	0.003±0.020	BDL	0.32	BDL	0.002±0.003	**0.00***	BDL	BDL	–
Pb	BDL	0.0001±0.0000	0.18	BDL	BDL	–	BDL	BDL	–	0.0001±0.0000	BDL	0.08
Hg	BDL	BDL	–	BDL	BDL	–	BDL	BDL	–	BDL	BDL	–
Coliform	3065.79±731.26		–	3602.63±1420.22		–	3734.21±935.86		–	17,692.11±16,707.20		–

*Significant difference ($p<0.05$); *BDL* Below Detection Limit

30.23 ± 0.17 °C, of which the highest was in March. Despite the variation, the temperatures during low and high tides of all seasons were within the suitable range for the growth of aquatic organisms (Boyd, 1998; Phu & Ut, 2006). Our previous studies in the border provinces of Can Tho city showed similar ranges of the temperature (25.96 to 31.20 °C) and pH (6.70 to 7.80) during 2018 to 2020 (Giao et al., 2021a, b and c), suggesting similar water quality in terms of these two parameters over the past few years.

In addition, the turbidity was significantly affected by the tide in all sampling months ($p < 0.05$, Table 3). The low-tide turbidity was significantly higher than the high-tide turbidity, which is possibly due to low dilution process (Ongley, 2009; MRC, 2015). The dilution effect was also shown by higher low-tide TSS values than the high-tide ones ($p < 0.05$). The TSS concentrations were ranging between 20.39 ± 4.83 and 61.93 ± 13.55 mg/L, which exceed the allowable limit of 20 mg/L (Table 1). In recent years, the surface water of bordering provinces of Can Tho city also showed TSS values exceeding the limit according to our previous studies (Giao et al., 2021c). The surface water bodies of An Giang and Dong Thap provinces, which are connected to Can Tho city at the north, showed similar TSS values of 41.16–48.67 mg/L in 2018 and 53.33–59.59 mg/L in 2020 for An Giang (Giao, 2020a; Hong & Giao, 2022) and 21.71–49.57 mg/L for Dong Thap (Giao et al., 2021c). It is worth mentioning that the ranges of TSS values found in these two provinces are less varied than the range observed in the surface water bodies of Can Tho city, which could suggest more variation of water pollution in this area. Other studies also found that TSS of other water bodies in the Mekong Delta exceeded the allowable limit of the same standard (Ongley, 2009; MRC, 2015; Lien et al., 2016; Giao & Minh, 2021). In this study, the TSS values in September and December were significantly higher than those in March and June, which could have resulted from an increase in the amount of water flowing and flooding from the upstream that contains high sediments in these months.

The effect of tide on organic pollution was determined from DO, BOD, and COD values. The DO content in the water bodies fluctuated in the range of 5.38 ± 0.21–6.05 ± 0.26 mg/L (Table 3). The DO values were comparable to or slightly lower than the permissible level (≥ 6 mg/L), suggesting the mild organic

pollution in water (Phung et al., 2015; Chounlamany et al., 2017; Zhang et al., 2020; Zoltan et al., 2021). This was also demonstrated by the BOD values in the range of 5.08 ± 1.10–8.32 ± 1.96 mg/L and the COD values in the range of 11.39 ± 2.43–16.11 ± 2.88 mg/L, which both exceed the allowable limit of QCVN 08-MT: 2015/BTNMT, column A1 (4 mg/L and 10 mg/L, respectively). These three parameters were significantly influenced by the changes of tides. The low-tide DO values were significantly higher than the high-tide ones since low tide normally occurs in the afternoon, which can limit the photosynthetic oxygen production (McKellar et al., 2007). High-tide BOD and COD concentrations were also lower than those during low tide. It can be seen that the effect of natural dilution during high tide could not reduce the organic pollutants to below the allowable limit. Our previous studies showed comparable DO values in the ranges of 5.29–5.56 mg/L in 2018 for An Giang (Giao, 2020a) and 4.73–5.55 mg/L in 2019 for Dong Thap (Giao et al., 2021c); however, these two provinces suffered more organic pollution than Can Tho city. The COD values of An Giang surface water increased from 11.68–13.54 mg/L in 2018 to 21.14–37.22 mg/L with the BOD values of 13.65–24.19 mg/L in 2020 (Giao, 2020a; Hong & Giao, 2022). In the case of Dong Thap province, the ranges of BOD and COD values were 12.75–18.00 and 20.00–25.75 mg/L in 2019, respectively (Giao et al., 2021c). Hau Giang province also had higher organic pollution in surface water than Can Tho city, which can be observed from the DO, BOD, and COD values of 3.20–5.20, 6.30–14.00, and 14.00–25.00 mg/L in 2019, respectively (Giao, 2020b). It should be noted that the different results between provinces can occur due to sampling year and parameters used for determining organic pollution, which relied on the resource availability and the monitoring projects conducted each year at each province. Nonetheless, it can still be seen that the provinces bordering Can Tho city has gradually suffered same organic pollution. Other studies also reported organic pollution problems in the surface water bodies of the Mekong Delta resulting from domestic, urban, and industrial wastewater (Atwebembeire et al., 2019; Ojok et al., 2017; Ongley, 2009; MRC, 2015; Lien et al., 2016; Giao & Minh, 2021). Stormwater runoff could also contribute to high organic content and high TSS concentrations, leading to the deterioration of surface water quality and the increased cost of feedwater treatment (Ongley, 2009; MRC, 2015; MONRE, 2018; Ratpukdi et al., 2019). Thus, it is expected that high organic content

will facilitate the growth of microorganisms. The results showed that the water bodies in Can Tho city were contaminated with coliform bacteria, exceeding the allowable limit of 2500 MPN/100 mL (QCVN 08-MT:2015/BTNMT, column A1) with the range of 3065.79 ± 731.26–$17,692.11\pm16,707.20$ MPN/100 mL. Our previous studies in bordering provinces found coliform contamination with wider ranges and higher maximum values in An Giang and Don Thap provinces, which showed 11,067.00–31,363.00 MPN/100 mL (Hong & Giao, 2022) and 1708.00–25,300.00 MPN/100 mL (Giao et al., 2021c), respectively. The coliform contamination was lower in Hau Giang province with the range of 1156.30–11,657.50 MPN/100 mL (Giao, 2020b). This could be due to the fact that Hau Giang province has smaller number of population and area compared with An Giang, Dong Thap, and Can Tho city, which leads to the lower amount of activities in the province contributing to coliform contamination.

The tidal effect on the nutritional parameters was found varying among the species of the compound. The $N–NH_4^+$ concentrations in the water bodies, ranging from 0.08 ± 0.03 to 0.25 ± 0.06 mg/L, were significantly higher during low tide than during high tide. The results also showed that $N–NH_4^+$ in the canals of Can Tho city was lower than that in other areas of the Mekong Delta. For example, $N–NH_4^+$ compounds had an average concentration of 0.27 ± 0.16 mg/L in the canals of Hau Giang province (Giao, 2020b), 0.30 ± 0.40–0.50 ± 0.50 mg/L in Tien Giang (Giao et al., 2021a), 0.36 ± 0.061–0.40 ± 0.074 mg/L in Dong Thap (Giao et al., 2021c), and 0.35–4.14 mg/L in Soc Trang (Tuan et al., 2019). In contrast, $N–NO_2^-$ concentrations were not significantly affected by tides, except in December where higher $N–NO_2^-$ concentration during low tide was recorded (Table 3). This is slightly higher than the $N–NO_2^-$ concentration found in Hau Giang province (0.01 ± 0.01–0.02 ± 0.01 mg/L) (Giao, 2020b). The $N–NO_2^-$ concentrations observed in both Can Tho city and Hau Giang are relatively small compared with those observed in Tien Giang province (0.00–0.20 ± 0.30 mg/L) (Giao et al., 2021a). According to the study by Koçer and Sevgili (2014), the concentration of $N–NO_2^-$ in water bodies usually fluctuates between 0.001 ± 0.001 and 0.022 ± 0.012 mg/L. High $N–NO_2^-$ concentrations have been observed in water bodies with high DO and low $N–NH_4^+$ (Ongley, 2009; MRC, 2015; MONRE, 2018). However, it should be noted that both $N–NH_4^+$ and $N–NO_2^-$ concentrations in the water bodies of Can

Tho city observed in this study were within the allowable limits of 0.3 and 0.05 mg/L, respectively (QCVN 08-MT:2015/BTNMT, column A1). Similar to the $N–NH_4^+$ concentrations, the $N–NO_3^-$ concentrations of 0.33 ± 0.13–1.08 ± 0.34 mg/L were also subject to tidal influence, in which the $N–NO_3^-$ concentrations during low tide were significantly greater than those during high tide. The range of $N–NO_3^-$ concentrations was within the allowable limit of 2 mg/L (QCVN 08-MT:2015/BTNMT, column A1), which was similarly observed in other areas of the Mekong Delta (Ongley, 2009; MRC, 2015; Lien et al., 2016; Giao, 2020b; Giao et al., 2021a, 2021c; Giao & Minh, 2021). For the $P–PO_4^{3-}$ concentration, a significant tidal effect was observed only in June, in which the dissolved phosphorus during low tide was higher than that during high tide. The $P–PO_4^{3-}$ concentrations in the study area were in the range of 0.05 ± 0.02–0.07 ± 0.03 mg/L, which was within the allowable limit of 0.1 mg/L (QCVN 08-MT:2015/BTNMT, column A1). The results were comparable to the values observed by other studies in the Mekong Delta: 0.02–0.47 mg/L in the canals of An Giang province (Ly & Giao, 2018) and 0.04–0.11 mg/L in the Hau River in the An Giang-Hau Giang section (). In the natural environment, $P–PO_4^{3-}$ is usually at very low concentrations, around 5–20 µg/L (Boyd & Green, 2002). Combined with the findings of the previous studies, it is found that the $P–PO_4^{3-}$ concentrations of surface water in the Mekong Delta region were higher than the background level, hence being an important environmental problem (Ongley, 2009; MRC, 2015; Lien et al., 2016; MONRE, 2018).

Heavy metal content in surface water was also evaluated in this study (Table 3). The Fe content in the canals of Can Tho city was within the allowable limit (0.5 mg/L), ranging from 0.09 ± 0.04 to 0.28 ± 0.10 mg/L. The Fe concentrations during low tide tended to be higher than those during high tide. However, the statistically significant difference between low tide and high tide was recorded only in September, which could be the result of intense dilution by a considerable increase in the amount of rainfall and water flow from upstream in September (National Center for Hydro-Meteorological Forecasting, 2020). The F^- concentrations fluctuated from 0.06 ± 0.06 to 0.27 ± 0.18 mg/L, not exceeding the allowable limit (1.0 mg/L). Significantly higher fluoride concentration was observed during low tide in December. Other heavy metals (Cr, As, Pb, and Hg) in surface water of Can Tho city were in very low

concentrations, mostly below the detection threshold of the analytical methods and equipment used in this study.

In summary, high tide mostly had the negative influence on the water parameters in surface water of Can Tho city, reducing their concentrations in water. However, it was suggested that the water bodies were contaminated with organic pollution according to the TSS, BOD, and COD values, in which the concentrations exceeded the allowable limits despite the dilution during the high tide.

Seasonal effect on surface water quality

Seasonal fluctuation of water parameters especially the organic ones, such as TSS, BOD, N–NH$_4^+$, N–NO$_3^-$, Fe, and coliform, have been reported in previous studies, which was due to the temporal changes in anthropogenic activities, hydrology, precipitation, and water flow rates (Ongley, 2009; MRC, 2015; Islam et al., 2017; Chounlamany et al., 2017). In this study, the temporal variation of surface water quality was determined by the CPI and OPI (Fig. 2). According to the CPI assessment (Fig. 2a), the surface water quality in Can Tho city showed seasonal fluctuation. The surface water bodies in March, June, and September were slightly polluted with the locations S11, S31, and S35 being assessed as moderately polluted, respectively. These locations were contributed by small rivers generated by residential areas and agricultural activities. The water quality in December was

mild to heavily polluted, of which about 39.5% of the locations (15 out of 38 sites) were moderately polluted and 7.9% (3 out of 38 sites) were severely polluted. The heavily polluted location was identified at location S30, which was strongly affected by residential activities. The OPI assessment (Fig. 2b) shows that the surface water quality was organically polluted all year round with the highest index in March, which reduced to the lowest in September before increasing again in December. Out of all locations, the extremely polluted water was observed in location S5 where it was highly affected by residential wastewater. This result is consistent with the previous discussion that the water quality in the study area was organically polluted due to low DO and higher TSS, BOD, and COD than the allowable limit (Table 3). Previous studies have shown that land-use type greatly impacts water quality, particularly residential and urban areas being the major contributor to surface water pollution (Giao et al., 2021a, 2021c; Islam et al., 2017).

The spatial variation of surface water quality in 38 water bodies of Can Tho city assessed by WQI is presented in Fig. 3. In March (Fig. 3a), excellent water quality was observed in 19 out of 38 locations, good water quality was observed in 18 locations, and only one location was observed with medium quality. In June (Fig. 3b), the water quality was excellent, good, and average at 22, 14, and 2 locations, respectively. In September (Fig. 3c), the water quality was excellent, good, and average at 24, 13, and 1 locations, respectively. It can be seen that the number of locations
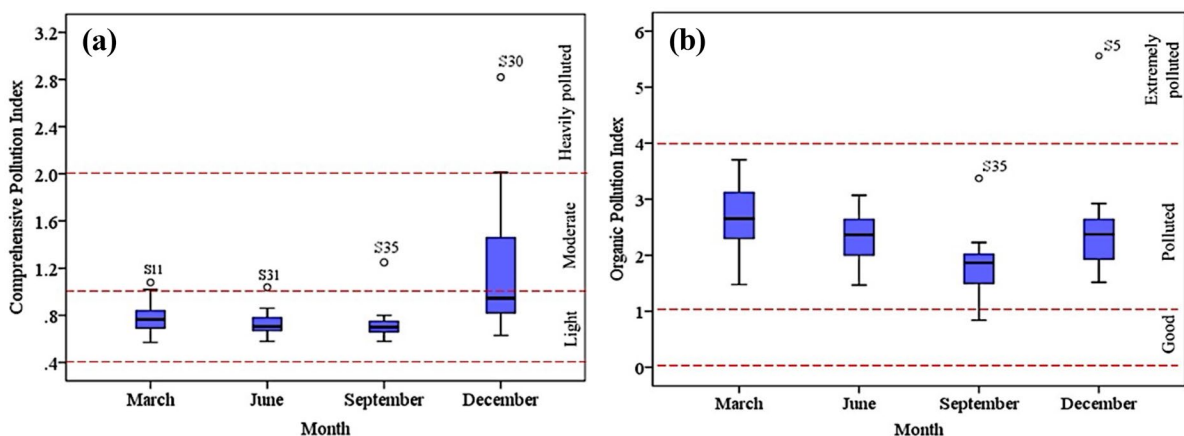

Fig. 2 Temporal variation of surface water quality classified by CPI (**a**) and OPI (**b**)
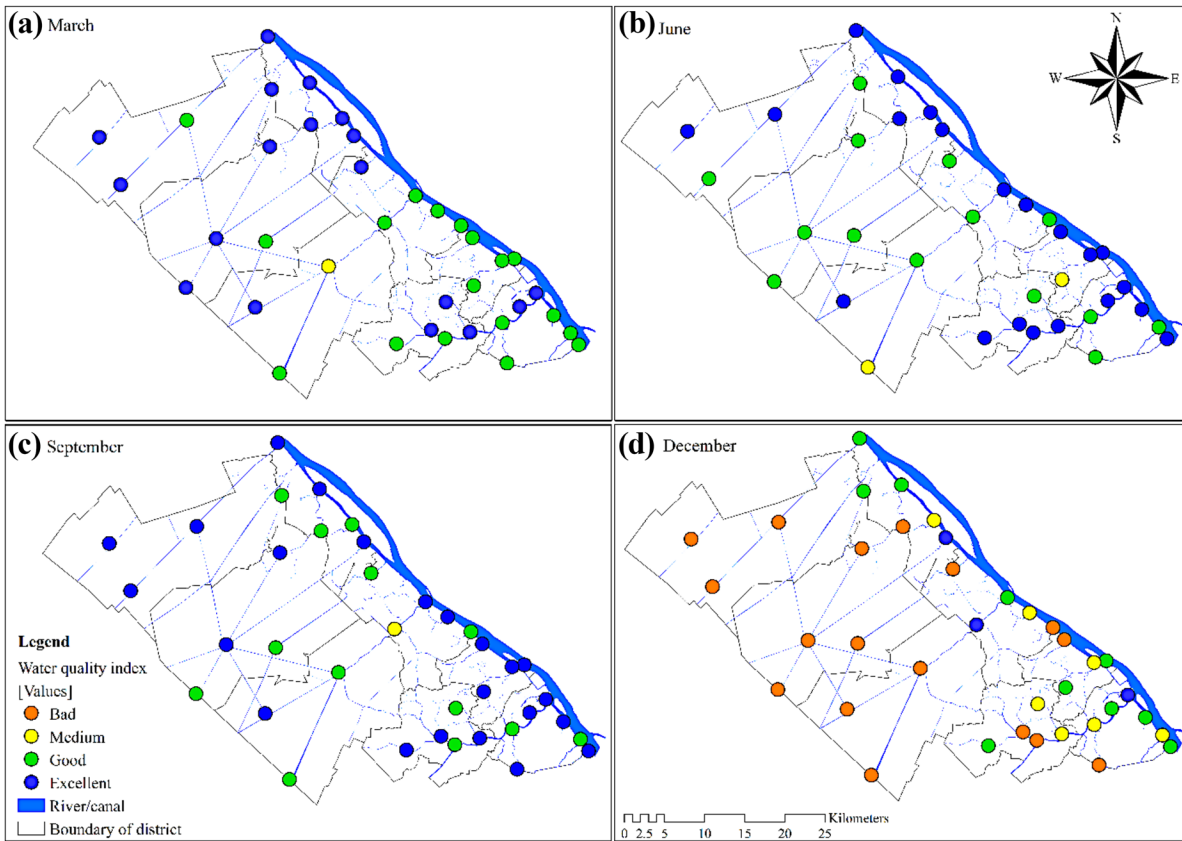
**Fig. 3** Spatial variation of surface water quality classified by WQI

with excellent water quality increased from March to September. However, in December (Fig. 3d), only 3 locations were observed with excellent water quality, and 11, 7, and 17 locations were found with good, medium, and bad water quality, respectively. According to the calculated WQI data, the water quality fluctuated greatly over time (Fig. 4), which also shows the lowest WQI and highest WQI variation in December. The seasonal variation determined by WQI is consistent with other seasonal variations observed by determining water quality parameters separately (Ongley, 2009; MRC, 2015; Islam et al., 2017; Chounlamany et al., 2017). This means that WQI can effectively summarize a large number of parameters into a single index to evaluate the overall water quality (Anh et al., 2020; Giao et al., 2021c). Similar to the WQI results, the CPI showed that the water quality in December was more polluted than the water quality in other months (Fig. 2). While the OPI showed high organic pollution in December, the most severe organic

pollution was observed in March. OPI is an important and useful index for assessing the water quality in the domestic water supply sector because organic substances in the input water can lead to the formation of disinfection by-products with chlorine, which can be precancerous compounds, seriously affecting human health (Ratpukdi et al., 2019). According to the results from this study, it is recommended that the assessment of surface water quality in similar cities of Vietnam or other countries should be assessed by the OPI index in addition to the WQI index.

Identification of key variables influencing the surface water quality

PCA method was employed to identify the indicators affecting the surface water quality of Can Tho city, which in turn helps to determine the possible pollution sources. The principal components (PCs) with an eigenvalue greater than 1 are considered the

Fig. 4 Temporal variation of WQI
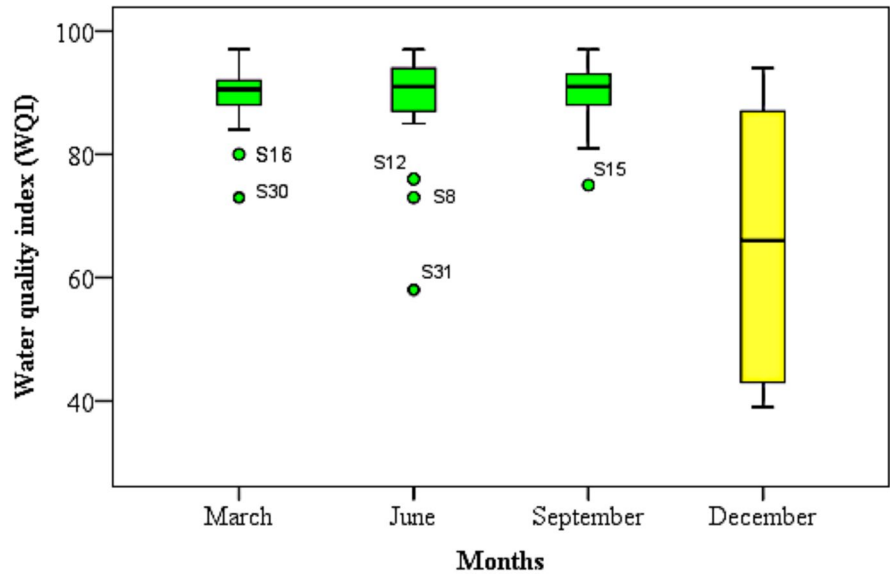
main components that significantly influence water quality variability (Chounlamany et al., 2017; Islam et al., 2017). From Fig. 5, 17 PCs obtained from the PCA method described 100% of the variation. The first five PCs (PC1–PC5) have been identified as having a great influence on the change of water pollution (eigenvalue > 1), which could explain 64.40% of the variation in water quality. This is in accordance with several previous studies that reported 5–6 PCs causing water quality fluctuations in similar water bodies (Giao et al., 2021a).

The correlation coefficients of water quality parameters and PCs are presented in Table 4. The analysis showed that PC1 has a weak positive correlation with temperature and pH while it has a weak

negative correlation with Cr, TSS, and Golia et al. (2015) also found that pH was negatively correlated with Fe content. Since the contents of Cr and Fe found in the study area were within the standard (Tables 1 and 3), it could be deduced that a major pollution in this PC is possibly from natural processes such as the leaching from Fe-containing soil and other suspended matter into water bodies (Nga and

Fig. 5 The eigenvalues and their percentage of variance of the PCs

Table 4 Loading values of parameters in PCA method

PC	PC1	PC2	PC3	PC4	PC5
pH	**0.31**	0.26	0.18	0.08	0.18
Temp	**0.43**	0.22	0.09	0.06	0.04
Turb	−0.13	**0.32**	−**0.40**	0.14	0.04
DO	−0.23	0.12	−**0.36**	−0.02	0.01
BOD	0.06	**0.47**	0.05	−**0.41**	−0.26
COD	−0.05	**0.39**	0.20	−**0.50**	−0.29
TSS	−**0.42**	0.14	−0.22	0.05	0.04
$N-NH_4^+$	0.12	**0.37**	0.23	0.24	0.27
$N-NO_2^-$	0.26	0.04	0.00	0.22	−0.09
$N-NO_3^-$	0.09	0.24	−0.21	0.32	−0.27
$P-PO_4^{3-}$	−0.05	0.18	**0.40**	0.33	−0.15
F^-	−0.25	−0.08	0.28	−0.05	−0.06
Fe	−**0.36**	0.08	0.24	0.06	0.16
Cr	−**0.31**	0.11	−0.20	0.19	−0.05
As	0.11	0.03	−0.04	−**0.35**	**0.69**
Pb	−0.03	0.22	**0.38**	0.27	0.20
Coliform	−0.27	0.28	0.02	−0.02	0.28

Thuy, 2011; Du et al., 2021). PC2 had a weak positive correlation with BOD, COD, N–NH$_4^+$, and turbidity. All of these parameters were mainly affected by urbanization including domestic and industrial wastewater discharge as observed in the previous study (Giao, 2020b). In addition, the positive correlation of turbidity to PC2 could be attributed to the disturbance by water transport, tides, and other surface currents. PC3 had a weak positive correlation with P–PO$_4^{3-}$ and Pb while it had a weak negative correlation with turbidity and DO. These parameters could be considered the effect of agricultural activities on surface water through erosion and agricultural runoff, which can contain high P–PO$_4^{3-}$ due to excessive fertilizer application. This source of pollution has also been reported in many previous studies in agricultural areas (Giao et al., 2021a; Su et al., 2011). Moreover, it was also suggested that fertilizer application can increase heavy metal content in soil (Nhien & Giao, 2019; Wang et al., 2016).

PC4 had a weak positive correlation with P–PO$_4^{3-}$, a weak negative correlation with As and BOD, and a moderately negative correlation with COD. This result indicates a decrease in both organic and inorganic matter content in water, so PC4 is more likely to be considered a source of decomposition of organic/inorganic substances in water (Peralta-Maraver et al., 2021). PC5 had a weak correlation with all water quality indicators but a moderate positive correlation with As. However, As concentrations in this study were reported at very low to undetectable concentrations. Therefore, As might not be affected by anthropogenic sources but could be

from atmospheric circulation, deposition, and rainwater (Qin et al., 2020). It should be noted that no significant correlation was observed for other pollutants such as N–NO$_2^-$, N–NO$_3^-$, F$^-$, and coliform even though the coliform data showed contamination in the water bodies of Can Tho. This contrasts with the studies in neighboring water bodies, which reported that the water bodies were mostly affected by coliform and N–NO$_3^-$ (Giao et al., 2021a; Phung et al., 2015).

According to the PCA results, the main parameters affecting the surface water quality of Can Tho city include pH, temperature, turbidity, TSS, DO, BOD, COD, N–NH$_4^+$, P–PO$_4^{3-}$, Cr, Pb, Fe, and As. Thus, these indicators are important and should be required in the monitoring of surface water quality of Can Tho city and other similar cities. Variation of natural processes, domestic wastewater, erosion, and leaching from agricultural land were possibly the main pollution sources affecting the water quality in the study area, even though several other pollution sources were identified in the analysis; however, they need to be investigated further in the field for specific identification in the future.

Quantitative evaluation for the contribution of each pollution source

The contribution of the pollution sources to each water quality parameter was conducted by the APCS-MLR method and the results are shown in Fig. 6. Most of the R^2 values ranged from 0.53 to 0.94 (except DO, N–NO$_2^-$, N–NO$_3^-$, F$^-$), which

Fig. 6 Contribution of pollution sources to the variation of individual water parameter
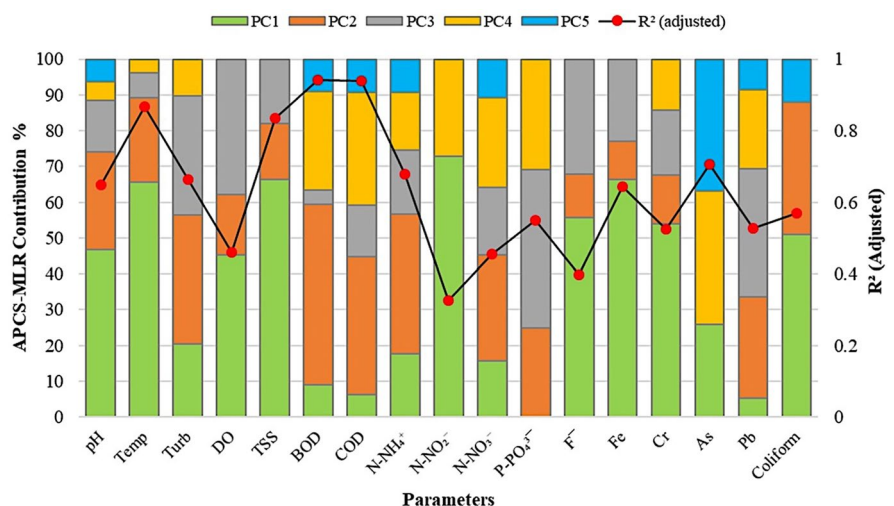
are higher than 0.5 and show that the APCS-MLR model has medium-to-high accuracy (Wang et al., 2016). Overall, the values of R^2 in APCS-MLR model analysis are consistent with the PCA analysis. In this study, most of the parameters were mainly affected by natural sources (PC1), untreated wastewater (PC2), and agriculture (PC3); this was expressed as a percentage of the contribution of the pollutant sources in the Y-axis (Fig. 6). The contribution of pollution sources to pH and temperature fluctuations ranged from 5.2 to 46.7% and 0 to 65.6%, respectively, in which the sources from natural processes had the greatest contribution. The main sources of turbidity variation were natural processes, and domestic and agricultural wastewater with an average value of 30% per source. Meanwhile, TSS showed that the variation is mostly caused by natural processes in the water, accounting for 66.5% of the total sources of volatility. Besides, two sources from natural processes (45.3%) and agriculture (37.8%) were the sources with the highest contribution to DO fluctuations. On the contrary, there was little change of BOD, COD, and $N–NH_4^+$ by natural elements since the pollution from untreated wastewater was the source that contributed significantly (38.5–50.3%) to the variation of this parameter. In addition, agriculture was also identified as a source of $N–NH_4^+$ contribution and volatility. On the other hand, the contribution rate of leaching and erosion of cropland (agricultural source) was identified as the main source for $P–PO_4^{3-}$ followed by the wastewater discharge from activities and decomposition of organic/inorganic substances containing phosphorus compounds. The fluctuations of heavy metals have been recorded mainly by natural transformation processes in water, in particular Fe (66.4%) and Cr (54.0%). For As, the model estimated that 74.2% of the variation was due to the decomposition of organic matter, atmospheric circulation, and deposition while Pb showed variation caused by agricultural sources (35.8%) and wastewater from operations (28.4%).

From the results, the water quality parameters had many different sources of pollution, causing the overall water quality variation in the study area. It was also found that the field monitoring parameters (pH, temperature, DO), TSS, and heavy metals are mainly controlled by natural factors while the remaining parameters are governed by human sources (livelihood and agriculture).

Conclusions

In summary, the surface water quality in Can Tho city has been contaminated with organic matter (low DO and high BOD, COD, and TSS) and microbiological pollution (coliform). Among the measured parameters, pH, turbidity, TSS, BOD, COD, $N-NH_4^+$, and $N-NO_3^-$, were significantly increased during low tide. The indices of water quality (WQI) and pollution (CPI and OPI) showed that water quality fluctuates greatly over location and time. The WQI index showed that overall water quality in December was more polluted than that in other months; however, the OPI index suggested that the organic pollution in March was more severe than that in the other months as observed. Therefore, it is recommended that the assessment of surface water quality in Vietnam should include the calculation of both WQI and the OPI indices. According to the APCS-MLR method, 64.40% of water quality variation in the surface water bodies of Can Tho city could be explained by five main components (PC1–PC5), which represent natural processes, wastewater from urbanization, agriculture, decomposition of substances by microorganisms, and atmospheric deposition, respectively. The main parameters that affect the water quality were pH, temperature, turbidity, TSS, DO, BOD, COD, $N–NH_4^+$, $P–PO_4^{3-}$, Fe, and As. Therefore, the suggestions from this study include the continuous monitoring of these indicators, the focus monitoring during the low tide, and the identification and restriction of pollution sources from urbanization and agriculture.

Author contribution N.T. Giao designed and directed the research and data collection. H.T.H. Nhien and P.H. Anh did the experiments and analyzed the data. P.T. Thuptimdang provided guidance and supervision for the research and the manuscript. All authors interpreted the data, discussed the results, and wrote the manuscript.

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

Declarations

Competing interests   The authors declare no competing interests.

References

Anh, N. M., Hang, N. T., Huyen, B. T., My, N. H., Hue, C. T., & Son, C. T. (2020). Assessment of An Duong lake water quality in Hai Duong province using a water quality index and water pollution indices. *TNU Journal of Science and Technology, 225*, 39–46. https://doi.org/10.3844/ajessp.2013.218.225

APHA; AWWA; WEF. (2012). *Standard methods of for the examination of water and wastewater* (22nd ed.). American Public Health Association.

Atwebembeire, J., Andama, M., Yatuha, J., Lejju, J. B., Rugunda, G. K., & Bazira, J. (2019). The physico-chemical quality of effluents of selected sewage treatment plants draining into river Rwizi, Mbarara municipality, Uganda. *Journal of Water Resource and Protection, 11*, 20–36. https://doi.org/10.4236/jwarp.2019.111002

Boyd, C. E., & Green, B. W. (2002). Water quality monitoring in shrimp farming areas: an example from Honduras, Shrimp farming and the environment. The World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment; Auburn: USA.

Can Tho Hydrological Station. (2020). *Documentation of water flow correction in 2020*. Can Tho, Vietnam: Can Tho Hydrological Station.

Can Tho's People Committee. (2020). Provincial environmental state report for the period from 2015–2020.

Chounlamany, V., Tanchuling, M. A., & Inoue, T. (2017). Spatial and temporal variation of water quality of a segment of Marikina River using multivariate statistical methods. *Water Science and Technology, 66*(6), 1510–1522. https://doi.org/10.2166/wst.2017.279

Du, J., Liu, F., Zhao, L., Liu, C., Fu, Z., & Teng, Y. (2021). Mercury horizontal spatial distribution in paddy field and accumulation of mercury in rice as well as their influencing factors in a typical mining area of Tongren City Guizhou China. *Journal of Environmental Health Science and Engineering*, *19*(2), 1555–1567. https://doi.org/10.1007/s40201-021-00711-z

Giao, N. T. (2020a). Evaluating current water quality monitoring system on Hau river, Mekong Delta, Vietnam using multivariate statistical techniques. *Applied Environmental Research*, *42*(1), 14–25. https://doi.org/10.35762/AER.202042.1.2

Giao, N. T. (2020b). Spatial variations of surface water quality in Hau Giang province, Vietnam using multivariate statistical techniques. *Environment and Natural Resources*, *18*(4), 400–410. https://doi.org/10.32526/ennrj.18.4.2020.38

Giao, N. T., & Minh, V. Q. (2021). Evaluating surface water quality and water monitoring variables in Tien River, Vietnamese Mekong Delta. *Jurnal Teknologi, 83*(3), 29–36. https://doi.org/10.11113/jurnalteknologi.v83.16355

Giao, N. T., Anh, P. K., & Nhien, H. T. H. (2021b). Spatiotemporal analysis of surface water quality in Dong Thap province, Vietnam using water quality index and statistical approaches. *Waters, 13*, 336. https://doi.org/10.3390/w13030336

Giao, N. T., Cong, N. V., & Nhien, H. T. H. (2021a). Using remote sensing and multivariate statistics in analyzing the relationship between land use patterns and water quality in Tien Giang province. *Vietnam Water, 13*(8), 1093. https://doi.org/10.3390/w13081093

Giao, N. T., Nhien, H. T. H., Anh, P. K., & Ni, D. V. (2021c). Classification of water quality in low lying area in Vietnamese Mekong Delta using set pair analysis method and Vietnamese water quality index. *Environmental Monitoring and Assessment, 193*(6), 1–16. https://doi.org/10.1007/s10661-021-09102-1

Golia, E. E., Dimirkou, A., & Floras, S. A. (2015). Spatial monitoring of arsenic and heavy metals in the Almyros area, Central Greece. Statistical approach for assessing the sources of contamination. *Environmental Monitoring and Assessment*, *187*, 399. https://doi.org/10.1007/s10661-015-4624-1

Hanh, P. T., Sthiannopkao, S., Kim, K. W., Ba, D. T., & Hung, N. Q. (2010). Anthropogenic influence on surface water quality of the Nhue and Day sub-river systems in Vietnam. *Environmental Geochemistry and Health, 32*(3), 227–236. https://doi.org/10.1007/s10653-009-9279-9

Hoang, H.T.T., Duong, T.T., Nguyen, K.T., Le, Q.T.P., Luu, M.T.N., Trinh, D.A., Le, A.H., Ho, C.T., Dang, K.D., Némery, J., Orange, D., & Klein, J. (2018). Impact of anthropogenic activities on water quality and plankton communities in the Day River (Red River delta, Vietnam). *Environmental Monitoring and Assessment, 190*(2), 67. https://doi.org/10.1007/s10661-017-6435-z

Hong, T. T. K., & Giao, N. T. (2022). Analysis of surface water quality in upstream province of Vietnamese Mekong delta using multivariate statistics. *Waters, 14*, 1975. https://doi.org/10.3390/w14121975

Islam, M., Lenz, O., Azad, A., Ara, M., Rahman, M., & Hassan, N. (2017). Assessment of spatio-temporal variations in water quality of Shailmari river, Khulna (Bangladesh) using multivariate statistical techniques. *Journal of Geoscience and Environment Protection, 5*, 1–26. https://doi.org/10.4236/gep.2017.51001

Kazi, T. G., Arain, M. B., Jamali, M. K., Jalbani, N., Afridi, H. I., Sarfraz, R. A., & Shah, A. Q. (2009). Assessment of water quality of polluted reservoir using multivariate statistical techniques: A case study. *Ecotoxicology and Environmental Safety, 72*(20), 301–309.

Koçer, M. A. T., & Sevgili, H. (2014). Parameters selection for water quality index in the assessment of the environmental impacts of land-based trout farms. *Ecological Indicators, 36*, 672–681. https://doi.org/10.1016/j.ecolind.2013.09.034

Lien, N. T. K., Huy, L. Q., Oanh, D. T. H., Phu, T. Q., & Ut, V. N. (2016). Water quality in mainstream and tributaries of Hau River. *Can Tho Scientific Journal of Science, 43*, 68–79. (In Vietnamese).

Ly, N. H. T., & Giao, N. T. (2018). Surface water quality in canals in An Giang province, Viet Nam, from 2009 to 2016. *Journal of Vietnamese Environment, 10*(2), 113–119. https://doi.org/10.13141/jve.vol10.no2.pp113-119

McKellar, H. N., Tufford, D. L., Alford, M. C., Saroprayogi, P., Kelley, B. J., & Morris, J. T. (2007). Tidal nitrogen exchanges across a freshwater wetland succession gradient in the upper Cooper River. *South Carolina. Estuaries and Coasts, 30*(6), 989–1006. https://doi.org/10.1007/BF02841390

Mekong River Commission (MRC). (2015). Lower Mekong regional water quality monitoring report. ISSN: 1683–1489. MRC Technical Paper No.51.

Ministry of Natural Resources and Environment (MONRE). (2015). *National technical regulation on surface water quality (QCVN 08–2015/BTNMT)*. Vietnam Environmental Protection Agency: Hanoi, Vietnam.

Ministry of Natural Resources and Environment (MONRE). (2018). *State of the National Environment in 2018-Water environment of river basins.* Vietnam Environmental Protection Agency: Hanoi, Vietnam.

National Center for Hydrometeorological Forecasting. (2020). *Long-term hydrological forecast bulletin for Central, Central Highlands and Southern rivers.* Hanoi: General Department of Meteorology and Hydrology.

Nga, T. T., & Thuy, V. N. (2011). Biological and environmental characteristics of Nelumbo nucifera, Nymphaea pubescens and Nymphoides indica in the National Park of Tram Chim, Tam Nong district, Dong Thap province. *Can Tho Scientific Journal of Science*, *23a*, 294–301.

Nhien, H. T. H., & Giao, N. T. (2019). Environmental soil, water, and sediment quality of Dong Thang landfill in Can Tho City, Vietnam. *Applied Environmental Research*, *41*(2), 73–83. https://doi.org/10.35762/AER.2019.41.2.7

Ojok, W., Wasswa, J., & Ntambi, E. (2017). Assessment of seasonal variation in water quality in river Rwizi using multivariate statistical techniques, Mbarara municipality, Uganda. *Journal of Water Resource and Protection, 9*, 83–97. https://doi.org/10.4236/jwarp.2017.91007

Oketola, A., Adekolurejo, S., & Osibanjo, O. (2013). Water quality assessment of river Ogun using multivariate statistical techniques. *Journal of Environmental Protection, 4*(5), 466–479. https://doi.org/10.4236/jep.2013.45055

Ongley, E. D. (2009). *Chapter 12: Water quality of the lower Mekong river*. In: Campbell, I.C. (ed.): The Mekong: Biophysical Environment of an International. https://doi.org/10.1016/B978-0-12-374026-7.00012-7

Peralta-Maraver, I., Stubbington, R., Arnon, S., Kratina, P., Krause, S., Cionek, V. M., et al. (2021). The riverine bioreactor: An integrative perspective on biological decomposition of organic matter across riverine habitats. *Science of the Total Environment, 772*, 145494. https://doi.org/10.1016/j.scitotenv.2021.145494

Phu, T. Q., & Ut, V. N. (2006). *Water quality for pond aquaculture*. Can Tho University: College of Aquaculture and Fisheries. 199 pp (in Vietnamese).

Phung, D., Huang, C., Rutherfordm, S., Dwirahmadi, F., Chu, C., Wang, X., et al. (2015). Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: A study in Can Tho City, a Mekong Delta area. *Vietnam. Environmental Monitoring Assessment, 2015*(187), 229–241. https://doi.org/10.1007/s10661-015-4474-x

Prathumratana, L., Sthiannopkao, S., & Kim, K. W. (2008). The relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River. *Environment International*, *34*(6), 860–866. https://doi.org/10.1016/j.envint.2007.10.011

Qin, G., Liu, J., Xu, S., & Wang, T. (2020). Water quality assessment and pollution source apportionment in a highly regulated river of Northeast China. *Environmental Monitoring and Assessment, 192*, 446. https://doi.org/10.1007/s10661-020-08404-0

Ratpukdi, T., Sinora, S., Kiattisaksiri, P., Punyapalakul, P., & Siripattanakul-Ratpukdi, S. (2019). Occurrence of trihalomethanes and haloacetonitriles in water distribution networks of Khon Kaen Municipality. *Thailand. Water Supply, 19*(6), 1748–1757. https://doi.org/10.2166/ws.2019.049

Son, C. T., Giang, N. T. H., Thao, T. P., Nui, N. H., Lam, N. T., & Cong, V. H. (2020). Assessment of Cau River water quality assessment using a combination of water quality and pollution indices. *Journal of Water Supply: Research and Technology-AQUA, 69*, 160–172. https://doi.org/10.2166/aqua.2020.122

Su, S., Li, D., Zhang, Q., Xiao, R., Huang, F., & Wu, J. (2011). Temporal trend and source apportionment of water pollution in different functional zones of Qiantang River. *China. Water Research, 45*(4), 1781–1795. https://doi.org/10.1016/j.watres.2010.11.030

Tuan, D. D. A., Thu, B. A., & Trung, N. H. (2019). Assessing quality of surface water for urban water supply source for Soc Trang City. *Can Tho Scientific Journal of Science, 4A*, 61–70.

Vietnam Environment Administration (VEA). (2019). *Decision 1460/QD-TCMT Dated November 12, 2019 on the issuing of technical guide to calculation and disclosure Vietnam water quality index (VN_WQI);* Vietnam Environment Administration: Hanoi, Vietnam.

Vietnam National Assembly. *Law on Environmental Protection* No. 77/2020/QH14 dated November 17, 2020, takes effect from January 1, 2022. 2020.

Wang, C., Yang, Z., Zhong, C., & Ji, J. (2016). Temporal–spatial variation and source apportionment of soil heavy metals in the representative river–alluviation depositional system. *Environmental Pollution, 216*, 18–26. https://doi.org/10.1016/j.envpol.2016.05.037

Wilbers, G. -J., Becker, M., Nga, L. T., Sebesvari, Z., & Renaud, F. G. (2014). Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. *Science of The Total Environment*, *485–486*, 653–665. https://doi.org/10.1016/j.scitotenv.2014.03.049

Zhang, H., Cheng, S., Li, H., Fu, K., & Xu, Y. (2020). Groundwater pollution source identification and apportionment using PMF and PCA-APCA-MLR receptor models in a typical mixed land-use area in Southwestern China.

Science of the Total Environment, 741, 140383. https://doi.org/10.1016/j.scitotenv.2020.140383

Zoltan, H., Mirjana, H., & Kristian, P. (2021). Assessment of spatial and temporal water quality distribution of lake Ludas, Serbia. *Environmental Science and Pollution Research*, *2021*, 1–33. https://doi.org/10.21203/rs.3.rs-637713/v1 (Preprint)