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Major concerns of surface water quality in south-west coastal regions of Vietnamese Mekong Delta

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Abstract

This study aimed to appraise seasonal variations in surface water quality on the coasts of Southwestern Vietnam using entropy-weighted water quality index (EWQI) and multivariate statistics: cluster analysis (CA), principal component analysis (PCA), and discriminant analysis (DA). Forty-nine samples monitored in Kien Giang province during the rainy and dry seasons were analysed for 16 physiochemical and biological parameters. Compared to the Vietnamese standard, surface water quality in the study areas was contaminated with organic matter (high biological oxygen demand and chemical oxygen demand), nutrients (high ammonium (NH_4^+), nitrite, and orthophosphate), total suspended solids (TSS), iron (Fe), and coliform. Seasonal variations in surface water quality in the coastal regions were observed. TSS, organic matter and microbial problems in water bodies tend to be more serious in the rainy seasons due to an increase in water flow containing pollutants from upstream and wastes from regional human activities. Meanwhile, the salinity in the dry season (0–32‰) was greatly higher, which caused only 10% of samples to be suitable for irrigation. CA extracted 11 and 13 clusters from 49 locations in the dry and rainy seasons, respectively. Five principal components obtained from PCA can explain 74 and 70% of total water quality variations in dry and rainy seasons, respectively. Moreover, the results of PCA suggested that natural factors (hydrological regimes, temperature, rainfall, sea-level rise) and human sources (domestic, agriculture, industry, and tourism) are accountable for these fluctuations. DA extracted 7 parameters (pH, TSS, salinity, Fe, nitrate, NH_4^+, and chloride) for leading the difference in water quality, with 88% of correct assignation. EWQI revealed that about 66% of total samples were classified as a very bad quality for drinking in the dry season. However, this ratio declined to 59% in the rainy season. Although the surface water quality was slightly improved during the rainy season, organic matter and microbial pollution need to be concerned. The findings of this study can provide insights into seasonal variations in surface water with the application of multivariate statistics and EWQI, which could support policymakers in developing water management strategies.

Keywords: Water quality, Entropy-weighted water quality index, Multivariate statistics, Coastal region, Mekong Delta

1 Introduction

Water is of paramount importance for human existence on Earth. It is an essential element to expedite socioeconomic development and maintain the balance of ecology [1, 2]. However, these human activities have caused negative impacts on water sources, particularly the pollution and depletion of surface water [3, 4]. For example, microbial and heavy metal contaminations have been observed in the Sisa river, Kumasi [1]. The urbanization and industrialization in 60 years seriously influenced the quality of river systems in Central Ethiopia [5]. Furthermore, surface water is widely used as feed water in drinking water treatment plants due to its availability and accessibility [6]. Thus, the deterioration of surface water

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quality is likely to threaten human health and increase the risks of water-borne diseases. In fact, using poor water quality is one reason for the high mortality rate (8.5%) in Southeast Asia [7].

In that context, surface water quality assessment has become an urgent and necessary task in every country. In addition to the impacts of anthropogenic activities, climate change is also responsible for the water crisis in many areas, especially the coastal regions where freshwater sources are susceptible to sea-level rise and human disturbance [8, 9]. Sea-level rise associated with global climate change has resulted in freshwater sources being salty and no longer suitable for domestic and production activities. In Vietnam, the sea level rose by about 14 cm between 1995 and 2019, and it was higher than 15 cm in 2020 using the Hon Dau 1992 datum [10]. Thus, seawater intrusion has deteriorated freshwater sources such as groundwater in Bac Lieu province [11] and in Soc Trang province [12], and surface water in Ca Mau peninsula [13]. While many studies have been published about water quality in Mekong Delta, most focused on assessing surface water quality along large rivers or recognizing potential pollution sources [14]. However, the surface quality in coastal regions has not received much attention.

In Vietnam, water quality monitoring has been enshrined in the law on environmental protection [15]. In the surface water monitoring program, different parameters have been measured to evaluate water quality: physical parameters (temperature, pH, electrical conductivity (EC), total suspended solids (TSS), turbidity, dissolved oxygen (DO)), chemical indicators (biological oxygen demand (BOD), chemical oxygen demand (COD), ammonium (NH_4^+), orthophosphate (PO_4^{3-}), heavy metals (iron (Fe), aluminum (Al), manganese (Mn), chromium (Cr), cadmium (Cd), chloride (Cl^- ion), sulfate (SO_4^{2-}), pesticides, antibiotics), and biological indicators (*Escherichia coli*, coliform) [16–18]. The selection of monitoring parameters and locations for surface water quality is decided on the basis of budget and characteristics of pollution sources. According to the Ministry of Natural Resources and Environment guidance, surface water quality is evaluated by comparing the values of parameters with the Vietnamese standard (QCVN 08-MT:2015/BTNMT) [19]. Additionally, the water quality index (WQI) is calculated to classify surface water quality [20]. However, these conventional methods have not been exploited all important information from the monitoring data sets; thus, their results are considered less objective. For example, in WQI calculation, weighting parameters or variables representing their importance is a crucial step that affects the comprehensive water quality assessment [21]. Nevertheless, these weights are commonly assigned based on the judgments of experts. Therefore, entropy weights based on information entropy have been introduced to improve the reliability of WQI application, which is defined as entropy-weighted water quality index (EWQI) [22, 23]. According to the information entropy, the weight of each parameter is determined based on the uncertainty of its concentration at the location [22]. Moreover, multivariate statistical tools, such as principal component analysis (PCA), cluster analysis (CA), and discriminant analysis (DA), have effectively interpreted the large data sets including many years, locations and parameters [5, 16–18]. CA is used to evaluate the efficiency of the monitoring network, such as the number of sampling locations, the frequency of monitoring as well as parameters. PCA yields principal components (PCs) from the original data set to determine parameters signifying variations of variables and to identify potential pollution sources [16, 17]. DA shows information about seasonal variations in water quality parameters [5]. Therefore, the objective of this study is to comprehensively evaluate the seasonal variations in surface water and recognize the potential pollution sources in Kien Giang province using these three aforementioned multivariate statistical approaches and EWQI.

2 Materials and methods

2.1 Study area description

Kien Giang is a coastal province in the Mekong Delta, Vietnam, with a natural area of 6348.78 km^2. Its geographical coordinates were from 9°3′20″-10°32′26″ north latitude and from 101°30′07″-105°32′06″ east longitude. It is bounded by Cambodia to the North, Ca Mau and Bac Lieu provinces to the South, and An Giang, Can Tho and Hau Giang provinces to the Northeast. The Southwest borders the Gulf of Thailand with over 200 km of coastline and islands. Kien Giang includes three main types of terrain: mountainous terrain (area of 7282 ha in the coastal area from Hon Dat district to Ha Tien city), island topography (including more than 140 islands in Kien Hai island and Phu Quoc city), and plain topography (with 3 typical ecological regions including Long Xuyen Quadrangle, West Hau River and U Minh Thuong). The province is located in the tropical monsoon climate characterized by high and stable temperatures all year round. Two distinct seasons are the rainy season (from May to November-coincides with the West and Southwest monsoons) and the dry season (from December to April next year-coincides with the East and Northeast monsoon seasons). The average annual air temperature during 2015–2019 was about 28.1 °C. The average annual rainfall during this period fluctuated around 1593 to 2630 mm. The peak month usually concentrates on July–October every year. The average number of rainy days is 175 d.

Moreover, the hydrological regime on the mainland is dependent on the tidal regime in the Gulf of Thailand, the hydrological regime in the Hau River and the in-field rainfall regime. This has created two distinct seasons of the hydrological regime, namely flood and dry seasons. Furthermore, due to the complex topography, the mountains are divided continuously, which establishes a complex system of streams and canals [24].

2.2 Sample collection and analysis

Forty-nine surface water points across 14 districts and cities of Kien Giang province were sampled in March (dry season) and September (rainy season) 2020. Samples were collected at estuaries, the beginning, middle, end of the river, and the confluences. GT (Giang Thanh river), HG1-HG3 (Ha Giang canal), KT3 (T3 canal), TN1-TN2 (Tam Ngan canal), TT1-TT2 (Tri Ton canal), BT1-BT2 (Ba The canal), RG1-RG4 (Rach Gia canal), CS1 and CS (Cai San river), K8 (8 canal), XXR1-XXR5 (Xang Xeo Ro canal), KX (Xang canal), MT (Miet Thu river), KH (Hau canal), LT71-LT72 (Lang Thu 7 canal), CB1 and CB2 (Chac Bang canal), VT (Vinh Thuan river), KS (Sang canal), BN (Ben Nhut canal), BS (Bong Sung canal), TN (Thot Not canal), KH6 (KH6 canal) were collected in inland water bodies. These places are representative for agricultural activities, especially rice and aquaculture farming. The locations CB1-CB4 (Cai Be river), BH (Ba Hoa canal), CL1-CL3 (Cai Lon river) belong to the estuary, river/canal, while positions RDD1-RDD2 (Dong Duong canal), CC (Cua Can river), RH (Ham canal), HDD (Dong Duong lake) are located in Phu Quoc island. Details of sampling locations are presented in Fig. 1. The measured water quality parameters included pH, temperature, EC, DO, TSS, salinity, Fe, COD, BOD, NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, total coliform, and Cl^-. The composite water samples were collected according to TCVN 6663–6:2018 and preserved according to TCVN 6663–3:2016. Some certain parameters (i.e., temperature, DO, pH, EC, salinity) were measured in situ, and other parameters were analyzed in the laboratory using standard methods [25]. The equipment and analytical techniques are given in Table S1. The analysis was performed in triplicate for each sample.

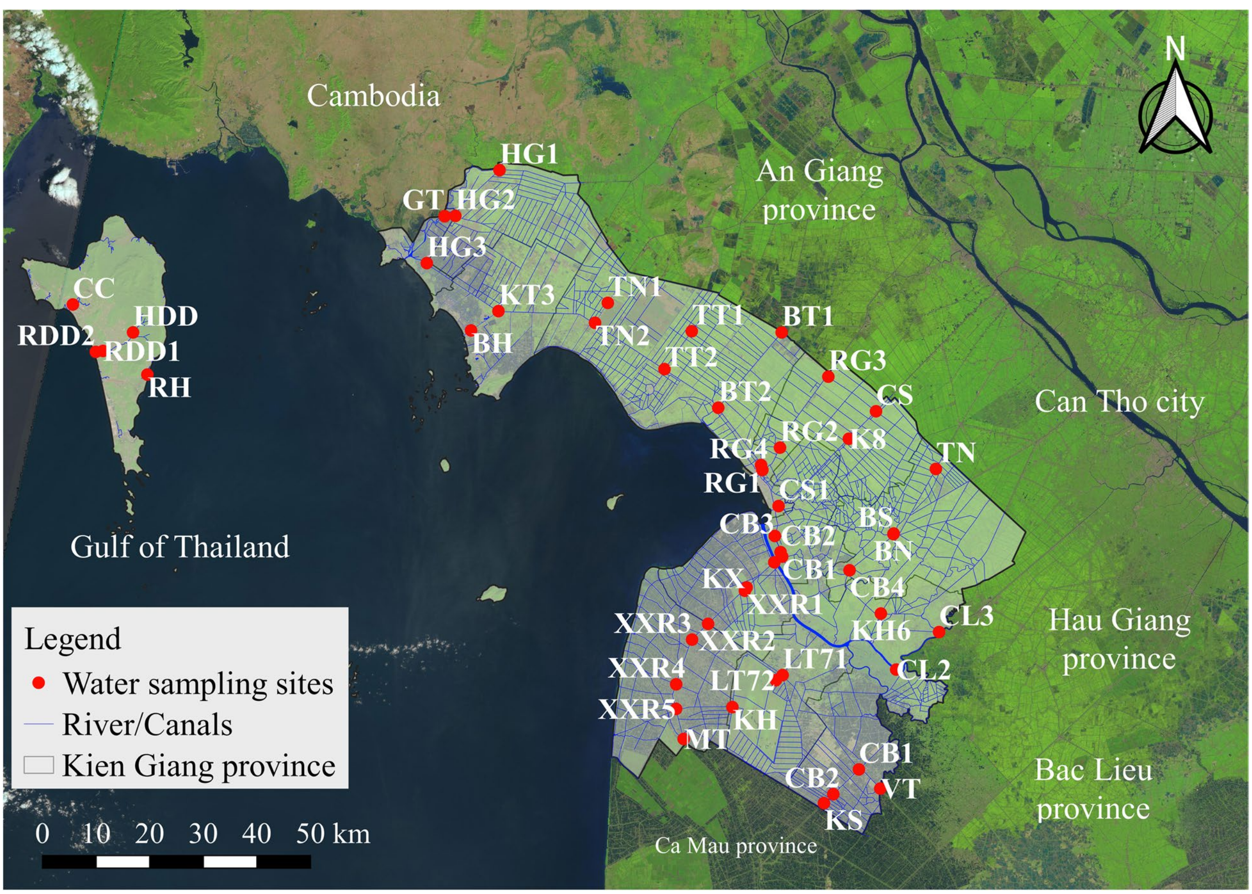

Fig. 1 Location map of surface water sample collection in Kien Giang province, Vietnam

2.3 Data analysis

2.3.1 Multivariate statistical methods

DA using forward stepwise modes was applied to establish discriminant functions (DFs) that distinguish parameters leading to seasonal variations in surface water quality. CA was applied to identify similarities in water quality between sampling locations using Euclidean distance [5]. PCA is another multivariate statistical analysis to determine the potential pollution sources and main parameters influencing surface water quality based on Eigenvalue and weighted correlation values [5, 26]. The weighted correlation coefficient was considered strong, moderate and weak, with absolute loading values > 0.75, 0.75–0.50 and 0.50–0.30, respectively [16]. These analyzes were performed using Statgraphics Centurion version XVI software (Statgraphics Technologies., Virginia, USA). The Kaiser–Meyer–Olkin (KMO) and Bartlett tests found the data set to be useful in PCA analysis. KMO values recorded in March and September were 0.64 and 0.67, respectively.

2.3.2 Entropy-weighted water quality index

EWQI calculation has been employed in previous studies [22, 23]. Firstly, the data is standardized using Eq. (1):

$$Y_{ij} = \frac{u_{ij} - (u_{ij})_{min}}{(u_{ij})_{max} - (u_{ij})_{min}} \quad (1)$$

where, u_{ij} is the concentration of parameter i at the sampling location j, $(u_{ij})_{max}$ and $(u_{ij})_{min}$ are the maximum and minimum values, respectively.

The ratio between the index values of parameter i in the sampling location j is then computed using Eq. (2):

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}} \quad (2)$$

The information entropy (E_{ij}) and entropy weight (w_i) are calculated using Eqs. (3) and (4):

$$E_{ij} = -\frac{1}{\ln m} \times \sum_{i=1}^{m} P_{ij} \ln P_{ij} \quad (3)$$

$$w_i = \frac{1 - E_{ij}}{\sum_{i=1}^{m}(1 - E_{ij})} \quad (4)$$

where, m is the number of sampling locations.

After obtaining the entropy weight of each parameter, EWQI is computed using the following formula:

$$EWQI = \sum_{i=1}^{n} w_i SI_i = \sum_{i=1}^{n}(w_i \times \frac{C_i}{S_i} \times 100) \quad (5)$$

where, n is the sum of the analyzed parameters i, w_i is the weight of the i^{th} parameter, SI_i is a sub-index of parameter i, C_i is the concentration of parameter i, S_i is the limit values of parameters for surface water quality in Vietnam [19]. The classifications of surface water quality based on the calculated EWQI values are presented in Table 1.

The ideal values of the parameters are all zero, except the ideal values of pH and DO are 7 and 14.6 mg L^{-1}, respectively [21, 27]. Therefore, the SI_{pH} and SI_{DO} values are calculated using Eqs. (6) and (7):

$$SI_{pH} = \begin{cases} \frac{C_{pH}-7}{8.5-7} & C_{pH} > 7 \\ \frac{7-C_{pH}}{8.5-7} & C_{pH} < 7 \end{cases} \quad (6)$$

$$SI_{DO} = \frac{C_{DO} - 14.6}{6 - 14.6} \quad (7)$$

3 Results and discussion

3.1 Surface water quality in Kien Giang province

3.1.1 Physiochemical and biological water quality parameters

The results of physiochemical and biological surface water quality parameters in March and September are illustrated in Fig. 2. pH values during the dry season (in March) ranged from 5.4–8.3, which was slightly higher than during the rainy season (in September) ranging from 3.3–7.9. Very low pH (3.3) was measured at KH where there is typical acidic sulfate soil. Thus, heavy precipitation or agricultural practices can lead to leaching sulfuric acid that lower pH in surface water nearby [28]. Additionally, the percentages of the sampling locations with pH values out of the Vietnamese standard (6–8.5) were 14.3% in March and 51.0% in September. This fluctuation in pH resulted from salinity, phytoplankton growth, and the discharge of alkaline water from agricultural areas [29, 30]. The great seasonal difference in surface water pH has been reported in Dong Thap province [30] and An Giang province [31].

There was little fluctuation in surface water temperature since water can regulate temperature, with an average of 29.3 °C in March and 29.2 °C in September. The average surface water temperature in Dong Thap ranged from 29.6–31.1 °C [30] and 30.1–30.7 °C in Tien Giang

Table 1 Scale and status of surface water quality using EWQI

Index range	Water quality status	Possible usage
< 50	Excellent	Excellent for drinking
50–100	Good	Good for drinking
100–150	Moderate	Domestic, irrigation, industrial
150–200	Poor	Not suitable for drinking
> 200	Extremely poor	Unacceptable

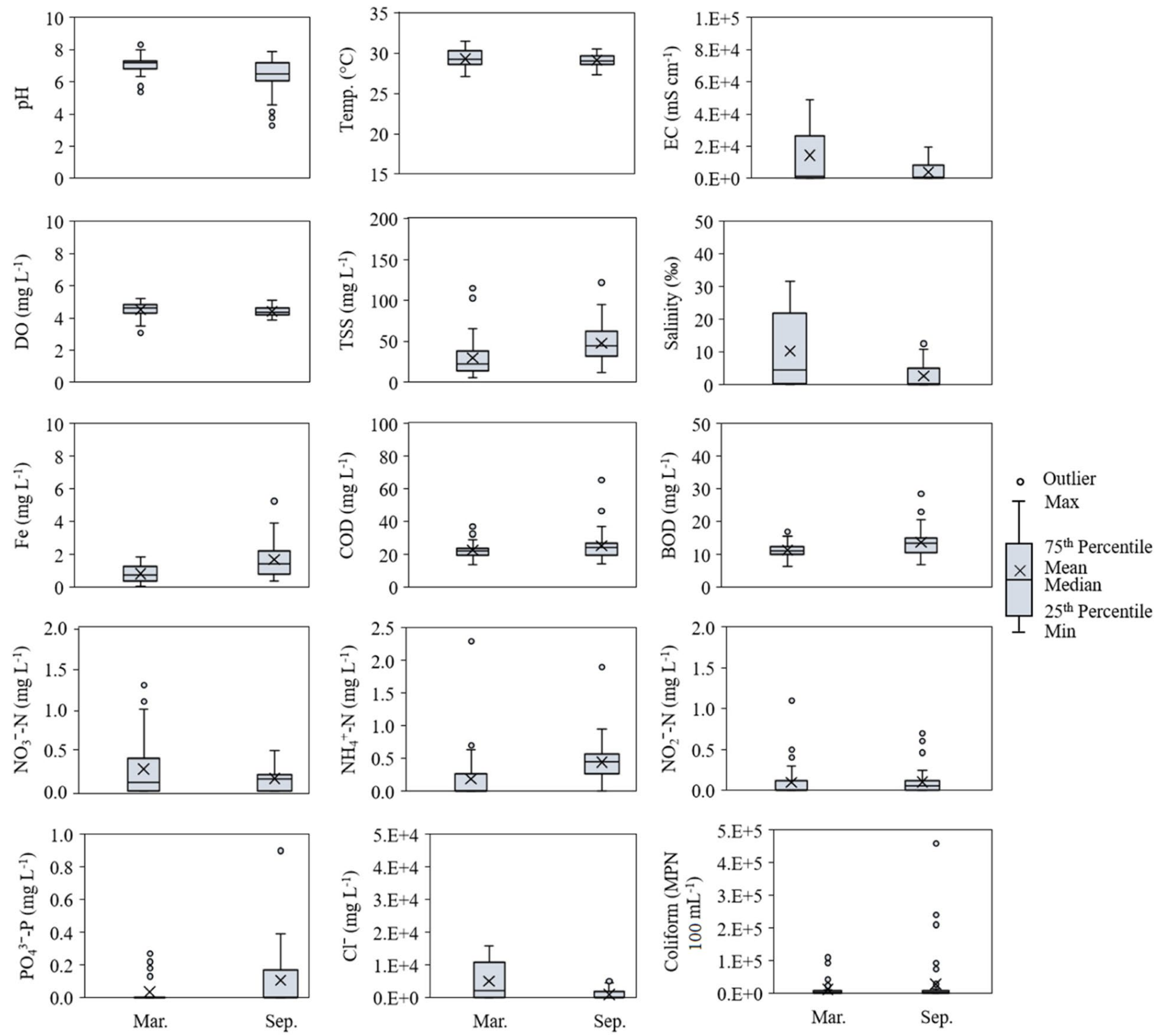

Fig. 2 Box-plot graphs of physiochemical and biological water quality parameters showing seasonal variations

[32]. The findings of Cl^- fluctuated in the range of 20–15,900 mg L^{-1} in the dry season and 16–6098 mg L^{-1} in the rainy season. These concentrations in Kien Giang province are higher than in other provinces in the Mekong Delta: 7.3–19.5 mg L^{-1} in Dong Thap [30] and 18.7–1250 mg L^{-1} in Tien River [33]. Cl^- detected concentrations were up to 9360 mg L^{-1} at sampling locations nearby the coast in Soc Trang province [2]. Similar to Soc Trang province, samples with high Cl^- concentrations were found at estuaries where seawater intrusion caused significant effects. The percentage of samples with Cl^- concentrations over the standard (250 mg L^{-1}) in the dry season was 61% higher than in the rainy season (37%). From January to May, the amount of water from upstream of the Mekong River decreases gradually, and the rainfall in the area also decreases, leading to a low water level in the canals. Thus, the tides in the Gulf of Thailand have facilitated saline water encroach deep into rivers and canals in the province [24].

The average concentrations of Fe (0.83 mg L^{-1}) and TSS (30 mg L^{-1}) in the dry season were lower than in the rainy season (1.69 mg L^{-1} of Fe and 48 mg L^{-1} of TSS), which exceeded the standards (0.5 and 20 mg L^{-1}, respectively). The average TSS concentration during 2011–2019 in the Tien River was 67 ± 3 mg L^{-1} [33]. Seasonal variations in TSS concentration were observed in the range of 22–50 mg L^{-1} in Dong Thap province [30]. The enrichment of Fe and TSS is related to water flow and flood from upstream, which can carry sediments and contaminants from domestic, industrial, and agricultural activities [30, 31]. The average DO in the dry and rainy seasons were 4.5 ± 0.4 and 4.4 ± 0.3 mg L^{-1}, respectively, which was lower than the limit (DO ≥ 6 mg L^{-1}). All samples with BOD and COD were over the limits (4 and 10 mg L^{-1}, respectively). The ranges of BOD (7–18 mg L^{-1}) and COD (14–37 mg L^{-1}) in the dry season were lower than in the rainy season (7–29 mg L^{-1} of BOD and 15–66 mg L^{-1}). These findings show the organic contamination of water bodies in the study area. In the Mekong Delta, a primary source of organic contamination is effluent from aquaculture activities [14]. Sampling locations with NH_4^+-N, NO_2^--N and PO_4^{3-}-P over the limits accounted for 69, 49 and 47% in the rainy season, respectively. These percentages were higher than in the dry season, with the values of 20, 43 and 20%, respectively. The average NO_3^--N concentrations were 0.27 ± 0.37 mg L^{-1} in the dry season and 0.16 ± 0.14 mg L^{-1} in the rainy season, which was within the limit. Sewage water and agricultural runoff containing fertilizers are the main sources of nutrients in water bodies [14]. Lower NO_2^--N and NO_3^--N can be caused by the low redox ability, and lower DO content is due to nitrification reaction [34].

The average coliform densities found in the dry and rainy seasons were 11,800 ± 22,800 and 28,500 ± 78,700 MPN 100 mL^{-1}, respectively, which was approximately 5 and 11 times higher than the limit (2500 MPN 100 mL^{-1}), respectively. Coliform contamination has long been a serious problem in surface water in the Mekong Delta. For example, coliform densities in the Tien River were continuously increased during 2011–2019, ranging from 2620–12,000 MPN 100 mL^{-1} [33]. In Dong Thap province, the findings of coliform and *E. coli* in the rainy season were higher in the dry season, with the values ranging from 4600–83,271 and 520–1729 MPN 100 mL^{-1}, respectively [31]. Coliform is an indicator of microbiological contamination resulting from untreated domestic sewage and non-point source of human and animal excretion [14, 35]. This can directly threaten human health. Thus, it increases water treatment costs once using this water source for recreational and drinking purposes.

3.1.2 Evaluation of the salinity distribution

The salinity distribution in surface water in dry and rainy seasons is presented in Fig. 3. The great spatial and temporal variations in surface water salinity were observed, except for locations RG2, RG3, CS, K8, and HDD. The findings of salinity varied between 0.0–32‰ in the dry season and 0.0–13‰ in the rainy season (Fig. 3). In the dry season, locations GT, HG3, CB1-CB3, CL1, XXR1-XXR5, LT71-LT72, CB1-CB2, VT, KS, RDD1-RDD2, CC and RH were heavily affected by salinity (Fig. 3a). Meanwhile, fewer locations (HG3, CB3, CL1, XXR1-XXR5, MT, KH, LT71-LT72, CB1-CB2, VT, KS) were contaminated with salinity (> 1‰) in the rainy season (Fig. 3b). According to Kotera et al. [29], the salt concentrations in the coastal zones of the Mekong Delta were detected up to 35‰. However, the findings in the inland areas in the delta were low. It is testament to the effect of seawater on the river systems in the study area.

Besides that, EC can also be used as an indicator of salinity in water [2]. The EC values fluctuated in the dry season greater than in the rainy season, with values of 8–49,100 and 158–18,600 μS cm^{-1}, respectively (Fig. 2). These are in agreement with the seasonal variations in salinity measured in the study area. The suitability of water salinity for agricultural cultivation on the basis of EC is presented in Table 2 [36, 37]. It can be seen that the high salinity in the dry season limits its use of surface water for irrigation in Kien Giang province. Only 10% of sampling sites with the salinity were completely suitable for irrigation, while samples with the salinity unsuitable for irrigation accounted for about 45%. Some locations need to select plant species with high salt tolerance to be able to adapt, accounting for 8%. In the rainy season, the ratio of samples with salinity entirely suitable for irrigation increased by 35%, and that of unsuitable ones decreased to 20%. This improvement can be explained by the distribution of precipitation and temperature during the year. Rainfall in Kien Giang province fluctuates greatly from 0.1–488 mm yr^{-1}, with an average rainfall of 200 mm yr^{-1}. This amount is low from December to April next year. Conversely, high rainfall starts from May to November. The peak of the rainy season is between July and September, as illustrated in Fig. 4. Thus, from the results of rainfall measurements, the weather in Kien Giang is divided into two distinct seasons, in which the rainy season from May to November is dry from December to April next year. An increase in rainfall and water flow from upstream with the potential to control salinity has also been reported in a previous study by Islam et al. [23]. Moreover, temperature fluctuations can also affect evaporation, leading to an increase in salinity in the water [38]. The temperature in Kien Giang province ranged from 26.4 to 30.2 °C, with an average of 28.3 °C. The temperatures in April and May reached the highest values (Fig. 4). Temperature tends to decrease gradually from June to November because of the rainy season.

However, in the rainy season, locations that want to cultivate must choose plant species with medium to

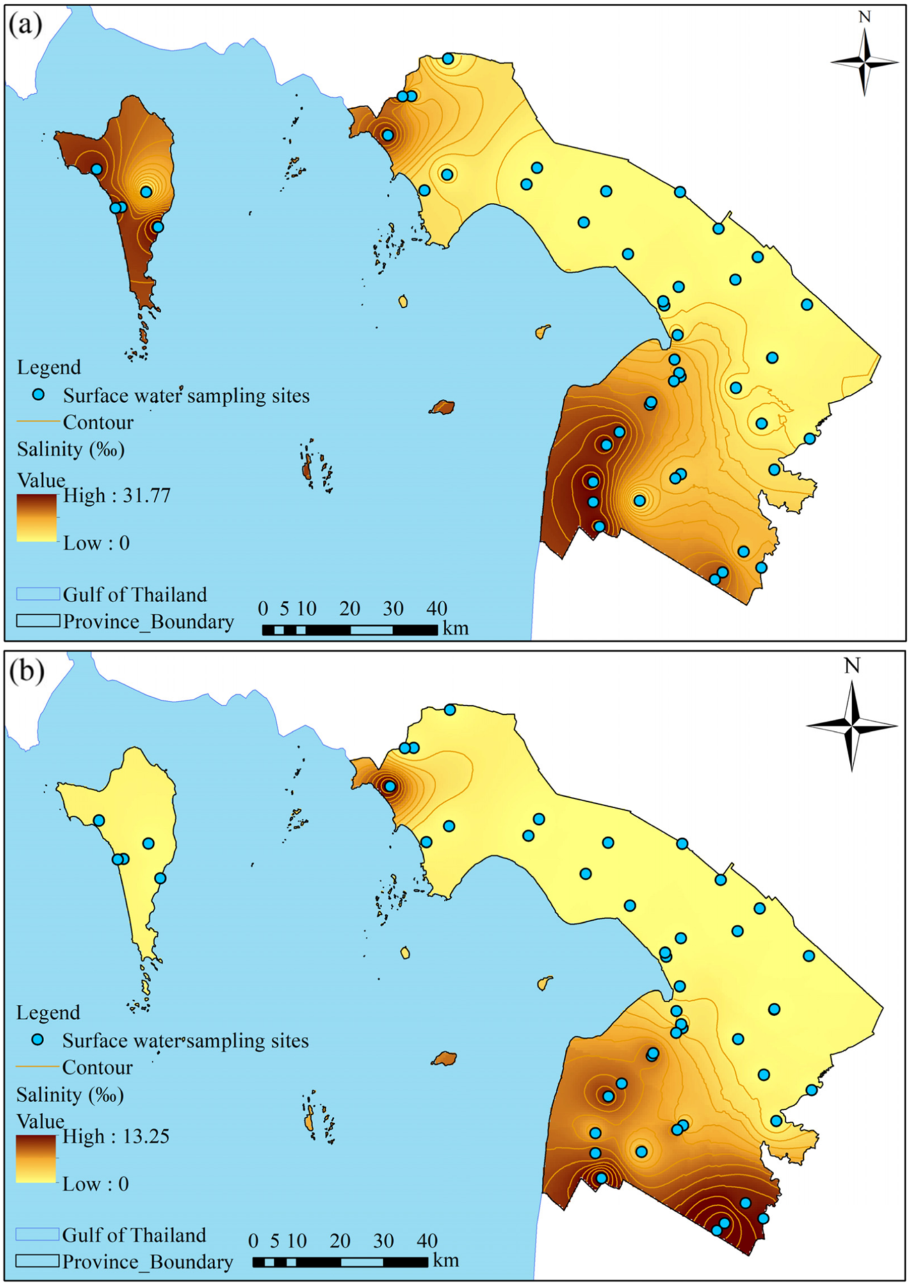

Fig. 3 Map of salinity distribution in (**a**) dry season and (**b**) rainy season of Kien Giang province

high salinity adaptability accounted for 16%. The EC contents in other water bodies were 0.02–0.46 ds m^{-1} in Tien Giang [32]. Higher EC values of water bodies were found in the coastal regions than inland due to higher salt contents from seawater [14]. It can be seen that the seasonal fluctuations of salinity, EC and Cl^- in the study area were in the same trend since these parameters are closely related. This correlation was also found in the study of Minh et al. [31] in An Giang province.

3.1.3 Clustering sampling locations

As presented in Fig. 5, all 49 monitoring sites were grouped into 11 clusters in the dry season and 13 clusters in the rainy season. The characteristics of surface water quality in the rainy season tended to fluctuate

Table 2 The suitability of EC for irrigation water

EC (μS cm^{-1})	Suitability for irrigation[a]	Number of samples			
		Mar	%	Sept	%
< 250	Entirely safe, suitable for all types of crops	5	10.2	17	34.7
250–750	Medium salinity, safe practices for crops	18	36.7	14	28.6
750–2250	Medium to high saline, safe at allowable limits for plants	2	4.1	4	8.2
2250–4000	High salinity, salt-tolerant crops can be grown	2	4.1	2	4.1
4000–6000	Very high salinity, only high salt-tolerant plants can be grown	0	0.0	2	4.1
> 6000	Unsuitable for irrigation	22	44.9	10	20.4

[a] Source [36, 37]:

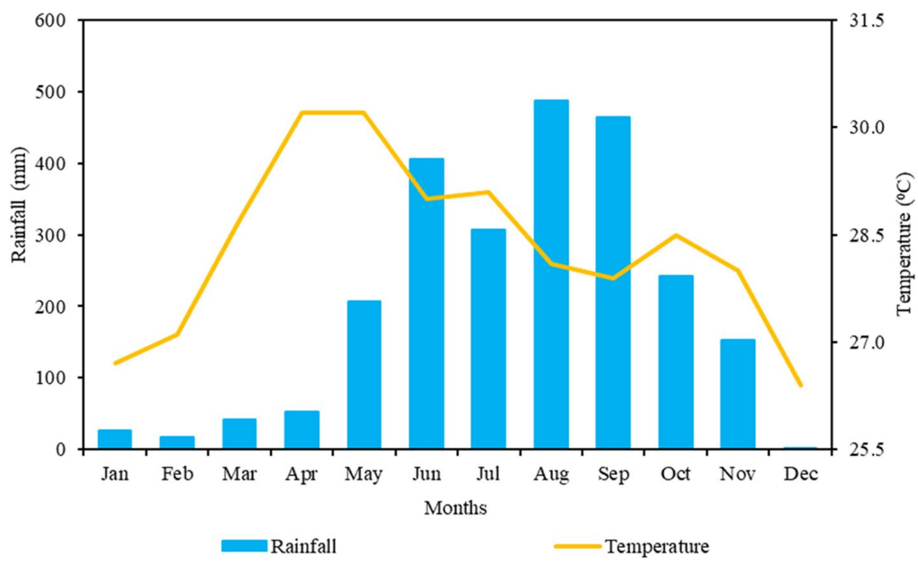

Fig. 4 Trends in ambient temperature and precipitation in Kien Giang province in 2020

between the sampling locations because of lower precipitation and water flow from upstream in the dry season. In March, cluster I included CS1, which was more heavily polluted by nitrite than other clusters. Cluster II comprised RDD1 characterized by the serious NH_4^+ and PO_4^{3-} contamination. These two clusters tended to be nutrient pollution related to agricultural runoff containing fertilizers and direct discharge of domestic sewage into water bodies. Cluster III comprised 4 sampling sites (CL1, CB1-3) that were seriously contaminated with BOD and COD. These points are located near the Tac Cau fishing port; thus, wastes from production activities at the port can contain high organic substances and consequently discharge into the nearby rivers and canals. Cluster IV covered 4 locations (RG1-3, CS), which showed more Fe contamination than other clusters. This is a result of natural processes and human activities (e.g., industrial effluents and corrosion of iron pipes) along both sides of the rivers. Cluster VI included 5 sites (BN, TN, BS, KH6, K8) found to be extremely polluted by TSS and coliform. These sites are located in Chau Thanh, Tan Hiep, and Go Quao districts. Three locations (BT1, BT2, TT1) were classified into cluster VII with very low DO and high NO_3^- concentrations. Cluster VIII included TT2, TN1 and TN2 with low pH in surface water compared to other clusters. Cluster XI comprised 8 sites (XXR2, XXR4, XXR5, MT, CB2, RDD2, CC, RH) characterized by high EC, salinity, and Cl^- concentrations. These sites are located in the Phu Quoc island and An Bien district that were easily influenced by sea-level rise. Clusters V, IX, and X included 5, 8, and 7 sampling locations, respectively. These were less polluted than other clusters. Based on

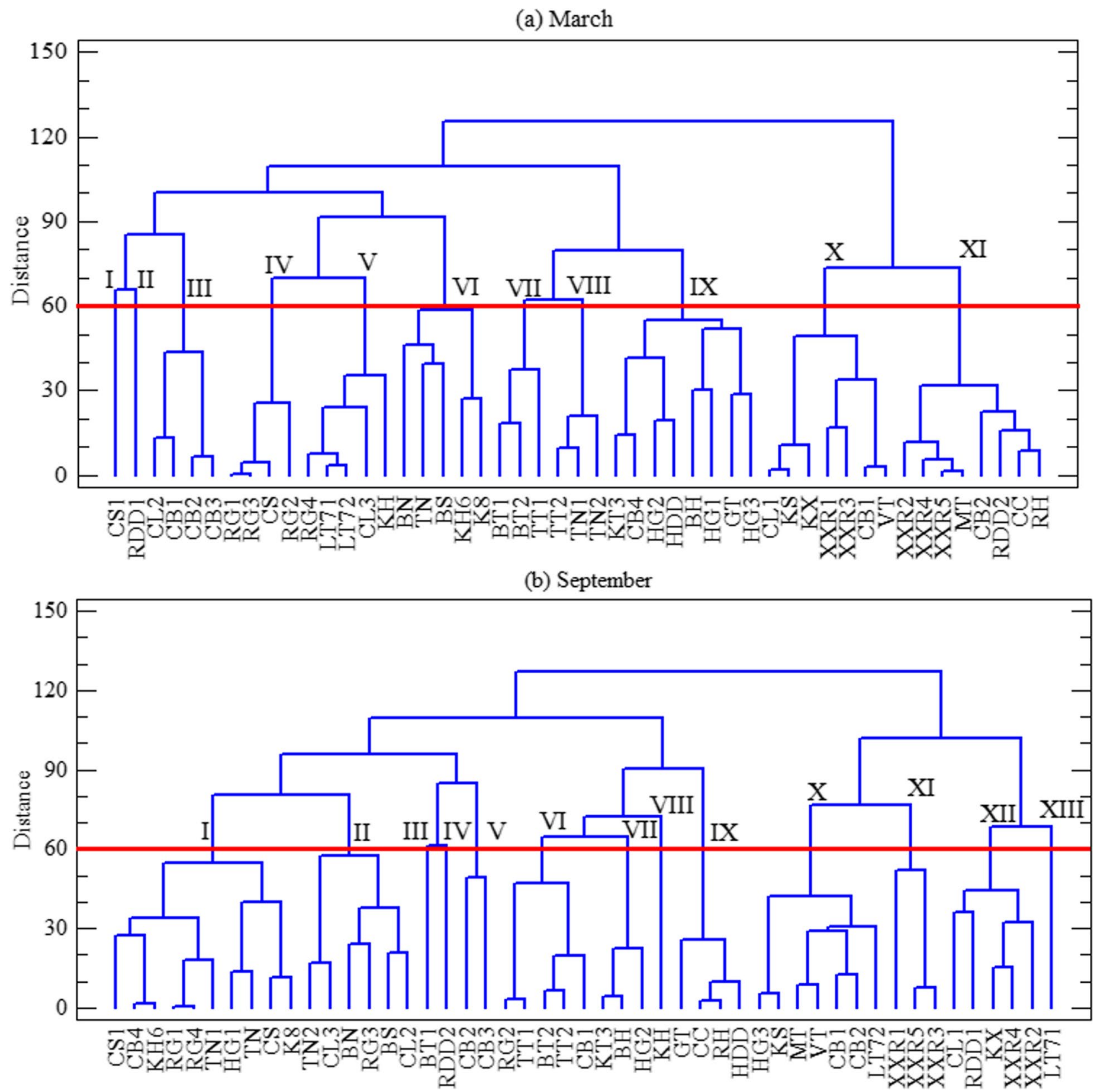

Fig. 5 Hierarchical dendrogram of sampling locations in (**a**) the dry season and (**b**) the rainy season

the characteristics of clusters and spatial distribution, the initial number of sampling sites can be reduced to 40 locations.

In September, clusters III and IV included BT1 and RDD2, respectively. These clusters were in turn described with heavy PO_4^{3-} and NH_4^+ contamination. Cluster V comprised 2 locations (CB2 and CB3) where serious coliform contamination was reported. Cluster VIII included only KH with very low pH and high Fe and NO_3^- contents in the canals. Seven locations (HG3, KS, MT, VT, CB1, CB2, LT72) were grouped into cluster X highly contaminated with EC, salinity and Cl^-. Cluster XI had XXR1, XXR3, and XXR5 with high NO_2^--N concentrations. Cluster XIII included only LT71 with serious organic contamination recognized by low DO and high BOD and COD. Clusters I, II, VI, VII, and XII comprised 10, 6, 5, 3,

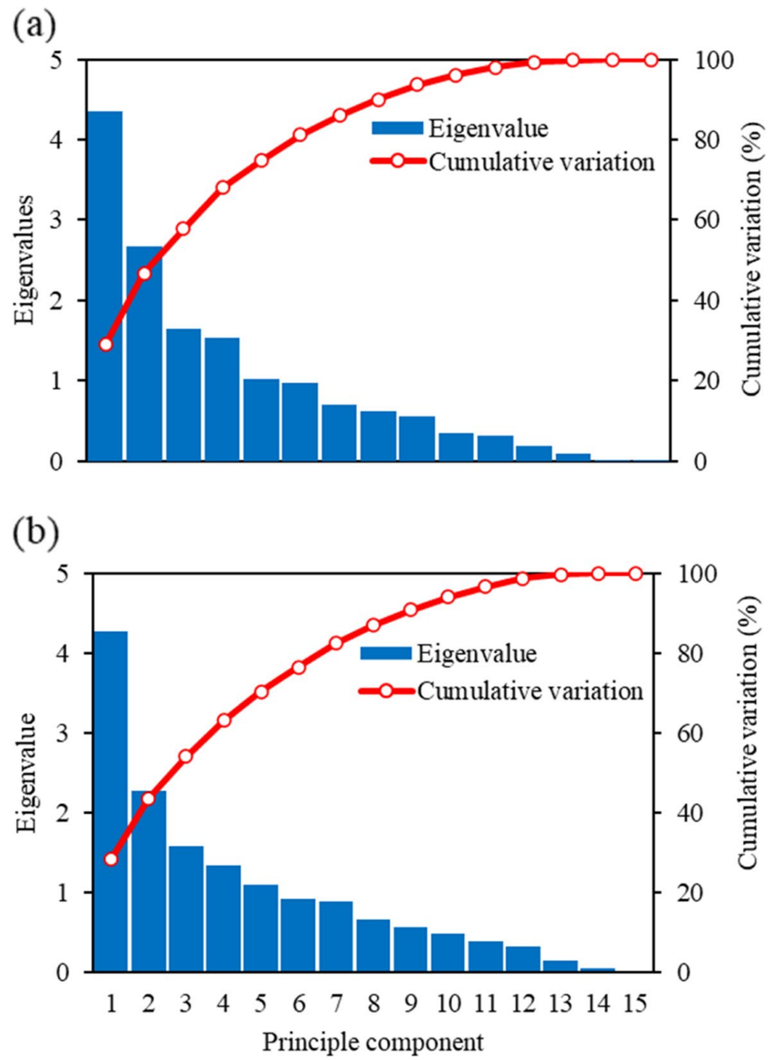

Fig. 6 Screening chart of principal components in (**a**) dry season and (**b**) rainy season

and 5 sampling locations, respectively. It is suggested that the number of monitoring sites can be reduced for spatial evaluation of surface water quality, which in turn lessens the costs of the monitoring program.

3.2 The principal factors affecting surface water quality

3.2.1 Identify the potential pollution sources

The results of PCA in water bodies of Kien Giang province are illustrated in Fig. 6, and the loadings of water quality parameters in each PC are given in Table S2. In the dry season, the total variation of water quality can be explained by 14 PCs, of which 5 PCs with eigenvalues greater than 1 are considered significant effects. These PCs can explain 75% of the variation in water quality (Fig. 6a). Over 29% of the total variations were explained by PC1. EC, salinity, and Cl^- formed weakly positive correlations, and there was a weakly negative correlation with NO_3^-. EC, salinity, and Cl^- were associated with sea level rise, tidal regime, and discharge from industrial wastewater. PC2 and PC3 could explain 18 and 11% of the variation, respectively. This PC had moderately positive correlations with COD and BOD, and a weakly negative correlation with temperature. Domestic and industrial wastewater and agriculture runoff are responsible for high values of COD and BOD. In PC3, there were weakly negative correlations with NH_4^+-N, PO_4^{3-}, NO_3^- and positive correlation with DO. Agriculture runoff, the application of fertilizer, and domestic

Table 3 The impacts of rapid socioeconomic development on surface water quality

Factor	Characteristics*	Impacts
Domestic activities	- Total wastewater volume: 160,060 $m^3\ d^{-1}$ (urban: 83,140 $m^3\ d^{-1}$ and rural: 76,920 $m^3\ d^{-1}$) Percentage of households with septic tanks: 75% - Total solid waste: 1,508 t d^{-1} (urban: 675 t d^{-1} and rural: 833 t d^{-1})	Reduce dissolved oxygen, organic pollution, phosphate, chloride
Agricultural, forestry and fishery activities	- Total estimated residues of fertilizers and chemicals: 1,970 kg d^{-1} - Wastewater: 7,530 $m^3\ d^{-1}$; waste: 814 t d^{-1} - The percentage of livestock households with hygienic barns is very low, only 15%	Eutrophication, causing odor and degradation of ecosystems in rivers and canals
Industrial activities	- Total industrial solid waste: 175 t d^{-1} - Wastewater: 8,190 $m^3\ d^{-1}$ - Industrial parks do not have centralized wastewater treatment systems	Eutrophication, highly toxic pollution, difficult to decompose
Tourism and travel-related services	- Wastewater flows from the service area: 10,380 $m^3\ d^{-1}$ - Amount of waste generated: 617 t d^{-1}	Contamination of organic matter and surfactants

wastewater are the primary sources of nutrients in surface water. The percentages of variance of PC4 and PC5 were 10 and 7%, respectively. These two PCs had a weakly negative correlation with pH and a positive correlation with PO_4^{3-}. While 4PC weakly correlated with temperature, PC5 had weak correlations with DO and TSS. Riverbank erosion was related to high TSS in surface water.

In the rainy season, the total variations in surface water quality in the study area can be explained by 15 PCs. 5 PCs (Eigenvalues > 1) explained 70% of the variation in water quality (Fig. 6b). PC1 had weakly positive correlations with EC, salinity, Cl^-, and NO_2^- and negative correlation with Fe. The natural processes and industrial activities can lead to an increase in Fe concentration in water bodies. It is similar to PC2 in the dry season; that is, PC2 in the rainy season had moderately positive correlations with BOD and COD. This PC can explain 15% of the variation of surface water in the rainy season. PC3, PC4, and PC5 can explain 11, 9, 7% of the total variation, respectively. There were positively weak correlations with DO and TSS and moderate correlation with temperature in PC3. These correlations were found in the PC5 in the dry season. Thus, heavy precipitation during the rainy season enhanced the transport of pollutants into water bodies and the impacts of riverbank erosion. Moreover, it can be deduced that the impact extent of potential pollution sources could change seasonally. In PC4, NH_4^+ had a moderate correlation, and PO_4^{3-}, DO and coliform weakly correlated. pH, temperature, Fe, NO_3^-, and NH_4^+ weakly correlated in PC5. Discharge from industry, agriculture, and domestic activities is the source of Fe, NO_3^-, and NH_4^+ in surface water [14].

3.2.2 Influence of social and economic development

Based on the results of PCA analysis, it can be seen that anthropogenic actions cause considerable impacts on water quality. Of various human impacts, four major socioeconomic development activities influencing surface water quality in the province are described in Table 3 [24, 39]. First, domestic activities can deteriorate water quality by discharging rich organic matter, nutrients, and chloride wastes. This has resulted in rapid oxygen depletion in the water. Second, agricultural, forestry, and fishery productions generate many nutrients and organic substances, leading to eutrophication. Moreover, industrial activities are characterized by toxic, non-biodegradable pollutants in addition to nutrients and organic matter. Lastly, tourism development activities emit many organic substances and surfactants [40]. Phu Quoc island in Kien Giang province

Table 4 Description of the significance level and discriminant function

	DF	Parameter	Standardized	Unstandardized
Eigenvalue	1.40	pH	0.33	0.40
Relative Percentage	100	TSS	-0.30	-0.01
Canonical Correlation	0.76	Salinity	-1.71	-0.19
Wilks Lambda	0.42	Fe	-0.49	-0.61
Chi-Square	81.04	NO_3^--N	0.86	3.11
DF	7	NH_4^+-N	-0.35	-0.99
p-Value	0	Cl^-	2.35	0.001
		(Constant)	0	-2.18

is a regional and international high-quality marine-based tourism. However, poor wastewater treatment and inefficient law enforcement have caused the deterioration of water quality [41].

3.3 Overall surface water assessment and classification

3.3.1 Temporal variations in surface water

The DFs and discriminant parameters between the two seasons through the stepwise forward mode in the DA analysis are presented in Table 4. The Wilks' lambda value (0.42) shows great discriminatory ability with a relatively high correlation coefficient (0.76). The results of DA revealed that the prediction efficiency correctly assigned 88% of the cases. The parameters that cause the difference in water quality between the two seasons include pH, TSS, salinity, Fe, NO_3^-, NH_4^+ and Cl^- because these parameters are all significant in the analysis ($p < 0.01$). The other parameters did not record significant seasonal

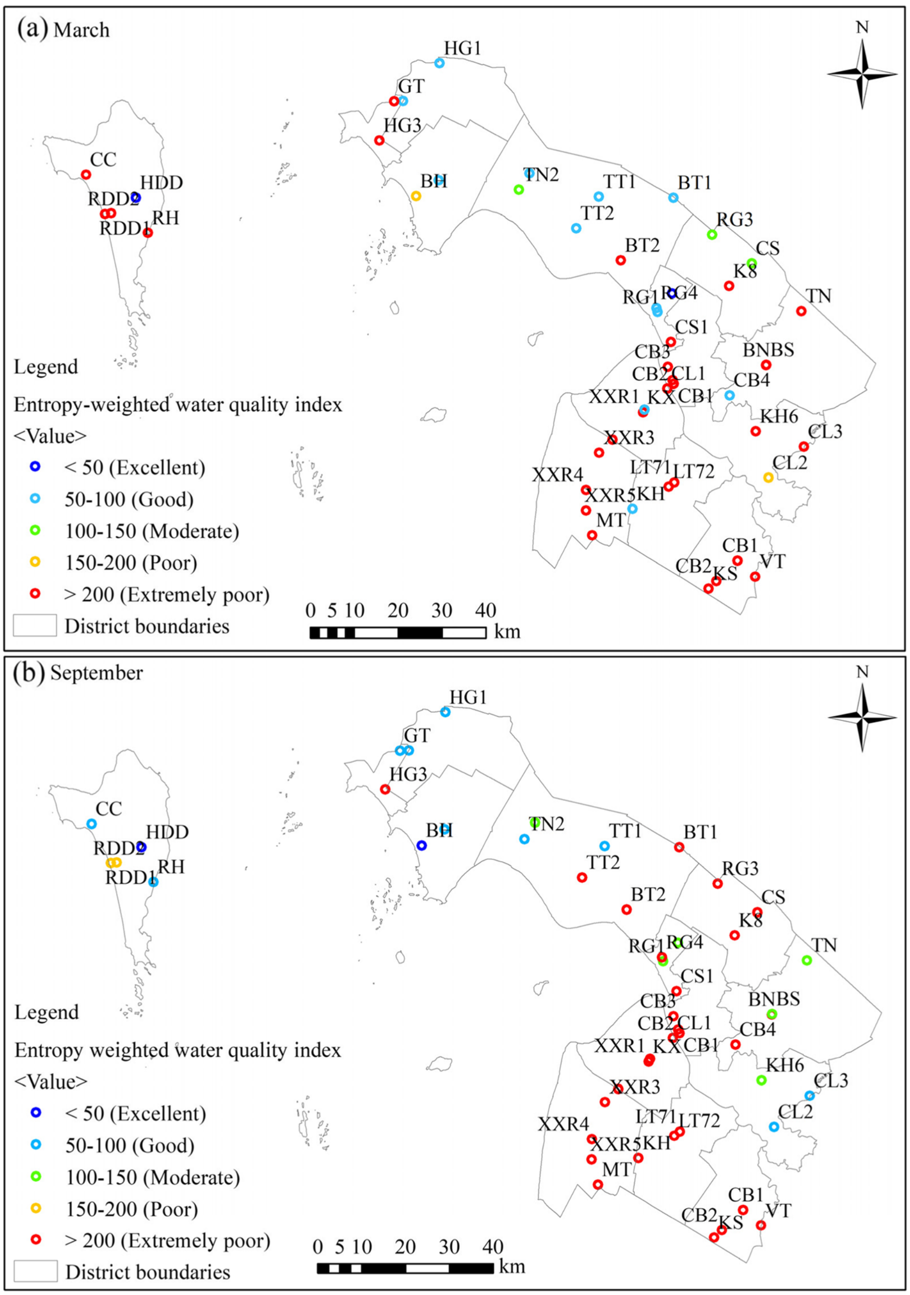

Fig. 7 Distribution of EWQI in (**a**) dry season and (**b**) rainy season in water bodies

variations. Specifically, the standardized coefficient reflected the order of importance of discriminant parameters, which means that parameters with positive values (pH, NO_3^-, Cl^-) are the most important parameters. The contributions of all three parameters pH, salinity and Cl^- show a significant temporal effect of sea-level rise. The equation for discriminating the change between the two seasons is shown in the equations below:

$$DF_{Standardized} = 0.33*pH - 0.30*TSS - 1.71*Salinity - 0.49*Fe + 0.86*NO_3^- - N - 0.35*NH_4{}^+ - N + 2.35*Cl^-$$

$$DF_{Standardized} = 0.40*pH - 0.01*TSS - 0.19*Salinity - 0.61*Fe + 3.11*NO_3^- - N - 0.99*NH_4{}^+ - N + 0.001*Cl^- - 2.18$$

From the relative magnitudes of the coefficients in the above equation, it is possible to determine how the independent variables are used to distinguish between the two seasons.

3.3.2 Water quality assessment

The values of EWQI revealed that water quality in the study area varied widely between monitoring locations and seasons (Fig. 7). The highest percentage of sampling locations in the dry season was classified as very bad water quality, accounting for 65% (32 out of 49 locations). Out of the total sampling points, 2, 10, 3 and 2 points were characterized by excellent, good, moderate, and bad water quality accounting for 4, 20, 6, and 4%, respectively (Fig. 7a). In the rainy season, surface water quality was slightly improved. The ratio of sampling locations with very poor quality was reduced to 59%, and that with moderate water quality increased to 12%. The percentage of locations with excellent water quality is the same as in March. The results of EWQI confirmed the seasonal and spatial variations in surface water in the study area again.

4 Conclusions

The study employed three multivariate statistical methods to examine spatiotemporal variations and recognize potential pollution sources of surface water quality in Kien Giang province in 2020. The results showed that the average values of TSS, BOD, COD, $NH_4{}^+$, $NO_2{}^-$, $PO_4{}^{3-}$, Fe and coliform far exceeded the Vietnamese standard for surface water quality. Only $NO_3{}^-$ was within the standard. Higher TSS, BOD, COD, and coliform concentrations were found in the rainy season. Only 10% of the sampling sites had water salinity completely suitable for irrigation in the dry season, while this number increased to 35% in the rainy season. The CA grouped the 49 monitoring sites into 11 and 13 clusters in the dry and rainy seasons, respectively. 5 PCs explain about 75 and 70% of the variation of surface water quality in the study area, respectively. The main drivers of water quality can be hydrological regimes, tides, agricultural activities, industry, services, and tourism. The results of EWQI revealed that the percentage of locations classified as excellent water quality accounted for only 25% in both seasons. The results of DA determined that the parameter causing the difference in water quality between the two seasons included pH, TSS, salinity, Fe, $NO_3{}^-$, $NH_4{}^+$, and Cl^-. The evidence suggests that the multivariate statistical methods and EWQI comprehensively interpret the large data sets and identify the pollution sources and factors influencing water quality variations, which benefits policymakers in planning water sustainable strategies.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-022-00156-5.

Additional file1: Table S1. Analytical techniques of surface water quality parameters and minimum detection limits (MDL). **Table S2.** Loadings of water quality parameters of significant principal components.

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Authors' contributions

Conceptualization, N.T.G. and H.T.H.N.; methodology, N.T.G.; software, H.T.H.N.; validation, N.T.G., H.T.H.N. and P.K.A; formal analysis, H.T.H.N.; investigation, N.T.G.; resources, N.T.G.; writing-original draft preparation, N.T.G., P.K.A and H.T.H.N; writing-review and editing, N.T.G and P.K.A; visualization, H.T.H.N.; supervision, N.T.G.; project administration, N.T.G. All authors read and approved the final manuscript.

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Competing interests

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