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Using Multivariate Statistical Methods to Identify Key Surface Water Pollutants in the Dry Season in a Coastal Province, Vietnam

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Abstract

This study was conducted to analyze water quality in a coastal province of Vietnam. Multivariate statistical methods, namely cluster analysis (CA) and principal component analysis (PCA) were utilized. Twelve parameters, namely pH, dissolved oxygen (DO), total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrite ($N\text{-}NO_2^-$), nitrate ($N\text{-}NO_3^-$), ammonium ($N\text{-}NH_4^+$), orthophosphate ($P\text{-}PO_4^{3-}$), chloride (Cl^-), iron (Fe), and coliforms were collected from ten locations in the 2020 dry season. The results showed that surface water was polluted by TSS, organic matters, nutrients, salinity, and coliforms compared to the national technical regulations on surface water quality (QCVN 08-MT: 2015/BTNMT). Cluster analysis results classified the original ten sampling locations into three groups due to BOD, COD, TSS, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, coliforms, and salinity. Principal component analysis (PCA) revealed that three principal components (PCs) could explain 84.5% of the variance of surface water quality parameters in the study area. Moreover, pH, TSS, DO, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, coliforms, and Cl^- were the key variables that influenced surface water quality in the dry season. The findings in this study can provide useful information for policymakers in developing programs of surface water quality management and protection.

Keywords

Bac Lieu, coastal water quality, organic matters, principal component analysis.

Introduction

Environmental water has been seriously affected by rapid An Giang province had concentrations of total suspended solids (TSS), biological oxygen demand (BOD), orthophosphate ($P\text{-}PO_4^{3-}$), and coliform that exceeded Vietnamese standards (Giao & Minh, 2021). Similarly, the surface water quality in Tien Giang province,

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Vietnam, was also contaminated by TSS, BOD, chemical oxygen demand (COD), ammonium ($N\text{-}NH_4^+$), $P\text{-}PO_4^{3-}$, coliforms, and *E. coli* because of the impacts of domestic and urban activities, industrial and agricultural effluents, and hydrological conditions (Giao *et al.*, 2021). Water quality is evaluated by comparing each water quality parameter with the national standard. This traditional method has not only been applied in Vietnam (Giao *et al.*, 2021; Giao & Minh, 2021) but also in other countries like Bangladesh (Howladar *et al.*, 2021) and China (Zhao *et al.*, 2012). According to the traditional assessment method, the parameters can lead to various results of water quality assessment; which can be confusing in terms of water management. Meanwhile, multivariate statistical methods such as cluster analysis (CA) and principal component analysis (PCA) have been widely applied to evaluate surface water quality (Zhao *et al.*, 2012; Hosseinimarandi *et al.*, 2014; Howladar *et al.*, 2021). These statistical methods are appropriate for dealing with multiple and varying parameters, providing comprehensive evaluation results, determining underlying relationships between the water quality parameters, and extracting important information from complex datasets (Zhao *et al.*, 2021). For example, multivariate analysis has been used to assess overall water quality by measuring the fluctuations in the water quality of rivers and lakes (Zhao *et al.*, 2012; Howladar *et al.*, 2021). Moreover, some previous studies have also used these effective multivariate techniques to identify the pollution sources and evaluate the monitoring network (Vega *et al*., 1998; Hosseinimarandi *et al*., 2014).

Bac Lieu province has one of the highest growth rates in the Mekong Delta region, and the economic growth rate in the period 2016-2020 was about 8.35% $year^{-1}$. The gross regional domestic product also continuously increased in these 5 years from 34.09 to 58.43 million VND $person^{-1}$. Agricultural farming has changed from traditional production to the application of advanced science and technology in farming, such as using alternate wetting and drying, and the IoT (Internet of Things). Industry and construction are exploiting their potential and strengths, especially in renewable energy, clean energy, and seafood processing. Similar to agriculture, production scales were expanded in various industries, and technological lines were improved and innovated. Therefore, the industrial production development index has increased gradually over the years. The export of seafood processing has become one of the key industries of the province, with 23 processing factories with a total capacity of about 135,000 tons $year^{-1}$. The garment sector has been gradually developing and creating jobs for more than 4,000 local workers. In industry, the amount of solid waste generated was about 67,395 tons $year^{-1}$; in which industrial parks/industrial clusters did not have centralized wastewater treatment systems. The total amount of water supplied and treated for waste and wastewater in industrial zones in 2019 increased by 4.01% compared to 2018 (Bac Lieu Statistics Office, 2019).

Fisheries have been identified as an important sector, accounting for 58% of agricultural products and nearly 21% of the provincial economy. The total production of aquaculture in 2019 reached 365,000 tons and the area was about 136,577 ha. Along with aquaculture, the fishing industry has also had good growth. The total output of aquaculture and fishing in the first six months of 2020 was 164,893 tons, with an average increase of 6.03% $year^{-1}$ in 2016-2020. In which, the area of industrial and semi-industrial shrimp farming was more than 20,000 ha, which generated about 2.6 billion m^3 of wastewater and 1.8 million tons of sludge per crop. Moreover, Bac Lieu, is also an attractive tourist destination in the Mekong Delta, welcoming over 2.7 million visitors in 2020 (People's Committee of Bac Lieu province, 2020). In addition, the total volume of domestic wastewater generated was approximately 74,476 m^3 day^{-1} (in 2019). This socio-economic development has led to the accelerating demand for freshwater for different human activities, and these activities have contributed to polluting water sources.

Therefore, this study was conducted to assess water quality by applying principal component and cluster analyses to identify the

main parameters affecting the variation of water quality and group sampling locations in Bac Lieu province. The research results could provide scientific information on the characteristics of water bodies in the study area.

Methodology

Study area

Bac Lieu province, a coastal province of the Mekong Delta, is located east of the Ca Mau peninsula, Vietnam. The province has a natural area of 266,900.08 hectares and coordinates from 9°0'0" to 9°38'9" north latitude and from 105°14'15" to 105°51'54" east longitude. Bac Lieu province shares borders with Hau Giang and Kien Giang provinces to the north and the northwest; Soc Trang province to the east and northeast; Ca Mau province to the west and southwest; and the East Sea to the east and southeast. Administrative units in the province include Bac Lieu city, Gia Rai town and 5 districts: and Hong Dan, Phuoc Long, Vinh Loi, Dong Hai, and Hoa Binh districts, with a total of 64 communes, wards, and towns. The terrain is relatively flat, and mainly situated at an altitude of about 1.2m above sea level. There are also dunes and some low-lying areas that are flooded all year round. The terrain tends to slope from the coast to inland, from the northeast to the southwest. The average slope of the whole province is from 1 to 1.5 cm km^{-1}, divided into two distinct topographical areas. The area north of 1A National Highway is a low-lying area of the province and has a low terrain with an average elevation above sea level from 0.2 to 0.6m, but some areas are below 0.2m, such as in Phuoc Long and Hong Dan districts. The area south of 1A National Highway has a higher terrain with discontinuous sea dunes and an average height from 0.4-1.3m, which is inclined and lower inland (People's Committee of Bac Lieu province, 2020).

Bac Lieu has a tropical monsoon climate with two distinct seasons: the rainy season from May to November, and the dry season from December to April. The average temperature throughout the year ranges from 26.35 to 29.16°C. The highest average temperature usually falls in March, and the lowest is in December. The average annual rainfall is over 1,700 mm $year^{-1}$. Specifically, rainfall is concentrated mainly in the rainy season (May-November), accounting for about 93% of the total annual rainfall; meanwhile, the rainfall in the dry season has been recorded as insignificant. This may affect the water quality of the area since this is a coastal area, which is very susceptible to saline intrusion. Specifically, the river and canal systems in the coastal area of Bac Lieu province connect to the East Sea by many gates, of which the three largest ones are Ganh Hao, Nha Mat, and Cai Cung. Tide characteristics are dominated by the irregular semi-diurnal tide regime in the East Sea (People's Committees of Bac Lieu province, 2020). The influence of rainfall, and tidal and river water regimes has led to seasonal variation in water quality in the study area. However, the study only focused on assessing water quality in the dry season because this period is the peak of saline intrusion in the locality and the water quality is significantly degraded (Center for Hydrometeorology Bac Lieu province, 2020), which seriously affects the daily activities of the people.

Data collection

In this study, surface water samples were collected from the main canals in Bac Lieu province, and the details are provided in **Table 1** and **Figure 1**.

The water samples were collected at ten locations in the dry season (March) in 2020. Each water sample collected was at least 30cm below the surface of the water. The collection bottle was submerged in the water body to ensure that the collected sample was homogenous and undisturbed. Then, the sample was labeled and stored at 4ºC according to the guidelines of the Ministry of Science and Technology (2018). These samples were analyzed for twelve parameters, namely pH, dissolved oxygen (DO, mg L^{-1}), total suspended solids (TSS, mg L^{-1}), BOD (mg L^{-1}), COD (mg L^{-1}), N-NO_2^- (mg L^{-1}), N-NO_3^- (mg L^{-1}), N-NH_4^+ (mg L^{-1}), P-PO_4^{3-} (mg L^{-1}), Cl^- (mg L^{-1}), Fe (mg L^{-1}), and coliforms (MPN $100mL^{-1}$) to evaluate surface water quality. The sample pH and DO values were

Table 1. Description of sampling locations

Site	Coordinates	Description
BL1	9°20'41.60"N 105°42'53.73"E	Cai Day canal, Chau Hung town, Vinh Loi district
BL2	9°10'27.77"N 105°16'45.41"E	Canal Xang Bac Lieu – Ca Mau, Hoa Binh town, Hoa Binh district
BL3	9°12'28.21"N 105°39'31.90"E	Canal 30/4, Vinh Hau commune, Hoa Binh district
BL4	9°26'10.56"N 105°27'36.65"E	Quan Lo Phung Hiep Canal, Phuoc Long town, Phuoc Long district
BL5	9°22'19.88"N 105°23'32.12"E	Pho Sinh crossroad channel, Phuoc Long commune, Phuoc Long district
BL6	9°15'32.84"N 105°32'50.84"E	Xom Lung Canal, Lang Tron ward, Gia Rai town
BL7	9°13'36.45"N 105°25'7.62"E	Outside Ho Phong sewer, Gia Rai town
BL8	9°07'53.58"N 105°29'28.90"E	Buu Hai Kenh Tu Canal, Dien Hai commune, Dong Hai district
BL9	9°09'15.95"N 105°31'48.16"E	Cau So 4 Canal, Long Dien Dong commune, Dong Hai district
BL10	9°07'47.21"N 105°17'1.45"E	Tac Van Canal, Lung Sinh hamlet, Dinh Thanh commune, Dong Hai district

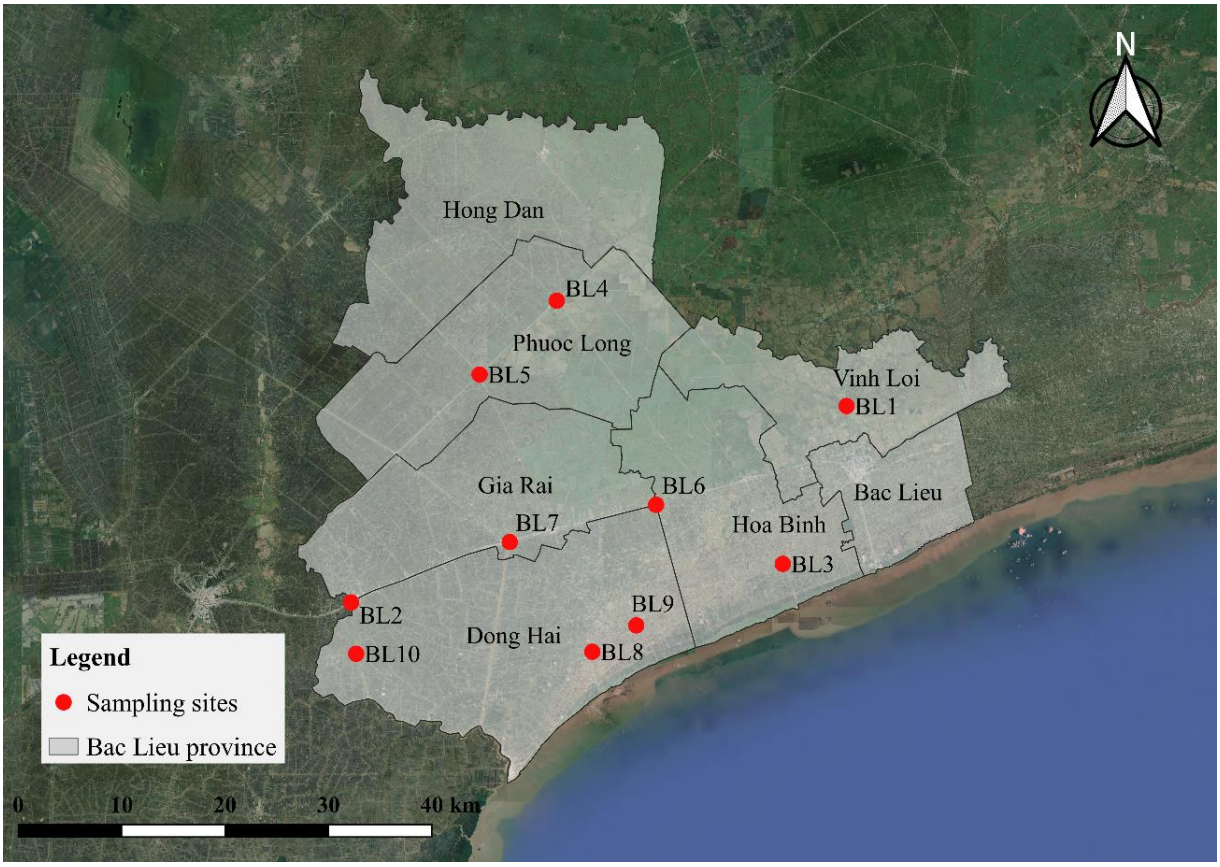

Figure 1. Location map of sampling sites in Bac Lieu province

determined in situ by hand-held devices, and the other parameters were analyzed in a laboratory using standard methods (American Public Health Association, 2017). Water sampling and analyses were conducted by the Department of Natural Resources and Environment of Bac Lieu province, Vietnam. The details of the analytical sampling methods are given in **Table 2**.

Data analysis

The National Technical Regulations on Surface Water Quality (QCVN 08-MT: 2015/BTNMT) was used to compare the parameter values to assess the water quality characteristics (Ministry of Natural Resources and Environment, 2015a). In addition, principal component analysis (PCA) was applied to reduce the data size, which had the objective of generating new variables, called principal components (PCs). Each PC was formed by the contribution of parameters and was expressed through the loading coefficient (Howladar *et al.*, 2021). In the PC, if a parameter had a larger loading factor than that of the remaining parameters, the contribution of that parameter to the PC was greater. This means that the loading coefficient can determine the parameters affecting the variability of the data.

Cluster analysis (CA) is a multivariate technique to group objects based on their characteristics. This method was implemented by arranging objects with the same properties into the same group, and the objects with different characteristics were grouped into other groups. Recognizing groups of the sample with similar water quality characteristics can be helpful in building future monitoring programs by reducing the number of monitoring sites. Moreover, it also benefits policymakers in developing surface water quality management policies (Singh *et al.*, 2004; Phung *et al.*, 2015). Ward's method and Euclidean distance were used to evaluate the distances between clusters (Zhou *et al*., 2007). CA and PCA were performed using copy-righted software Primer 5.2 for Windows (PRIMER-E Ltd., Plymouth, UK).

Results and Discussion

Evaluation of surface water quality in the dry season in Bac Lieu province

The pH was recorded from 7.12 to 8.38, ranging from neutral to slightly alkaline (**Table 3**). The results could be because of the mixing between river water and seawater, which is prevalent at the mouths of rivers. The pH was 6.60-8.1 in My Thanh River and Hau River

Table 2. Limited values of the surface water quality variables

Variable	Unit	Analytical method	Limited values*
pH	-	Determined by hand-held devices	5.5-9
DO	mg L^{-1}	Determined by hand-held devices	≥ 4
COD	mg L^{-1}	SMEWW 5220C:2017	30
BOD	mg L^{-1}	SMEWW 5210B:2017	15
TSS	mg L^{-1}	SMEWW 2540D:2017	50
$N\text{-}NO_2^-$	mg L^{-1}	SMEWW 4500-NO_2.B:2012	0.05
$N\text{-}NO_3^-$	mg L^{-1}	SMEWW 4500NO_3-E: 2017	10
$P\text{-}PO_4^{3-}$	mg L^{-1}	SMEWW 4500P-B&E:2017	0.3
$N\text{-}NH_4^+$	mg L^{-1}	SMEWW-4500-NH_3.F:2012.	0.9
Fe	mg L^{-1}	SMEWW 3500-Fe.B:2012	1.5
Cl^-	mg L^{-1}	SMEWW 4500.Cl^-.B:2012	350
Coliforms	MPN 100mL^{-1}	SMEWW 9221.B:2012	7,500

*Note: * Limited values are from column B1 of the National Technical Regulations on Surface Water Quality (QCVN 08-MT: 2015/BTNMT).*

estuary in Soc Trang province (Giang *et al.*, 2020), 7.00-7.80 in Can Tho city (Mekong River Commission [MRC], 2015), 7.0 ± 0.1 in Hau Giang province (Giao, 2020), and 6.53-8.02 in Ben Tre province (Giao & Minh, 2021). In general, the pH did not differ from previous reports and was within the allowable limit of QCVN 08-MT:2015/BTNMT, column B1.

The DO ranged from 4.25 to 5.55 mg L^{-1} (**Table 3**). In which, there were five sampling sites, namely BL2, BL3, BL6, BL7, and BL8, that had lower DO values than the other locations. However, the DO at all the survey sites reached the allowable value reported in column B1 of QCVN 08-MT:2015/BTNMT. The DO concentration in Tien River over nine years ranged from 4.8-6.9 mg L^{-1} (Giao & Minh, 2021). In the canals of Soc Trang province, the DO was lower than in other studies and ranged from 1.7-6.17 mg L^{-1} (Dinh Diep Anh Tuan *et al*., 2019; Giang *et al.*, 2020). The DO in rivers depends on diffusion, and the presence of phytoplankton and organic matter (Mekong River Commission, 2015). DO can be used as an indicator of the presence of organic contamination because microorganisms need oxygen to decompose organic matter (Giao *et al*., 2021). According to Ongley (2009), DO in surface water should be kept at least 5.0 mg L^{-1} to minimize the negative effects on the development of aquatic organisms. However, the average DO of all the studied locations was above this threshold.

The COD ranged greatly from 21.3 mg L^{-1} (BL1) to 602.6 mg L^{-1} (BL3) (**Table 3**). The COD exceeded the value specified in column B1 of QCVN 08-MT:2015/BTNMT from 8 to 21 times, except at location BL1. This COD value was higher than that of Ben Tre province by 7.21-59.74 mg L^{-1} (Giao & Minh, 2021), Tien Giang province by 14.4 ± 4.8 to 17.3 ± 4.4 mg L^{-1} (Giao *et al*., 2021), the Hau Giang canals by 17.9 ± 4.3 mg L^{-1} (Giao, 2020), and the My Thanh River and Hau River estuary (Giang *et al.*, 2020). High COD in the surface water is influenced by several social-economic activities such as restaurants, intensive urban areas, and industrial areas. COD is the amount of dissolved oxygen to oxidize chemical organic substances; that is, COD can be used to indicate the organic waste concentration in water (Kazi *et al*., 2009).

The BOD in the surface water environment in the study area fluctuated greatly, from 13.8 mg L^{-1} (BL1) to 410 mg L^{-1} (BL3). This result was consistent with that of the COD. At all locations, the COD was 1.5 times greater than the BOD. This ratio indicates the presence of recalcitrant organic compounds in the surface water in the study area. In former studies, the BOD was 2.2-22.4 mg L^{-1} in Soc Trang province (Dinh Diep Anh Tuan *et al*., 2019; Giang *et al.*, 2020), 10.5 mg L^{-1} in the Hau Giang canals (Giao, 2020), and

Table 3. Values of water quality at the ten monitoring sites in Bac Lieu province in the 2020 dry season

Variables	BL1	BL2	BL3	BL4	BL5	BL6	BL7	BL8	BL9	BL10
pH	7.12	7.65	7.7	7.15	7.34	7.95	7.74	8.38	8.37	7.81
DO	5.14	4.25	4.62	5.2	5.55	4.4	4.62	4.4	5.1	4.82
COD	21.3	522.6	602.6	240	293	549.3	469.3	389.3	384	442.6
BOD	13.8	356	410	164	195	372	292	262	260	300
TSS	68	267	364	15	43	146	121	1,024	1,429	424
$N\text{-}NO_2^-$	0.02	0.10	0.15	0.13	0.23	0.06	0.07	0.01	0.13	0.06
$N\text{-}NO_3^-$	0.68	2.86	2.63	3.81	1.53	4.47	3.51	5.28	4.55	5.55
$P\text{-}PO_4^{3-}$	0.02	0.32	0.28	0.01	0.02	0.30	0.19	0.16	0.18	0.17
$N\text{-}NH_4^+$	1.25	0.85	0.62	1.19	0.66	0.40	0.06	0.03	0.04	0.02
Fe	0.38	1.04	1.27	0.18	0.18	0.49	0.25	1.38	1.82	1.54
Cl^-	397	17,646	19,355	19,639	19,497	21,128	19,710	18,575	19,497	18,717
Coliforms	9,500	3,600	2,100	9,300	4,400	2,900	3,900	3,400	3,400	3,400

8.0 ± 2.7 to 8.9 ± 2.6 mg L^{-1} in Tien Giang province (Giao *et al*., 2021). It can be seen that the BOD in the freshwater areas was lower than that in the coastal areas. High BOD is a common problem in water bodies in the Mekong Delta (Mekong River Commission, 2015; Ly & Giao, 2018; Giao, 2020; Giao & Minh, 2021). Untreated waste from farming, livestock, landfills, domestic activities, and services has been discharged into the surface water environment, which has resulted in high BOD concentrations (Mekong River Commission, 2015; Chea *et al*., 2016).

The TSS in the study area was from 15 mg L^{-1} (BL4) to 1,429 mg L^{-1} (BL9) (**Table 3**). The TSS at the BL1, BL2, BL3, BL6, BL7, BL8, BL9, and BL10 locations tended to be higher than the limit published in QCVN 08-MT: 2015/BTNMT (column B1), from 1.4 to 8.5 times. In the Tien River, the TSS for the past nine years ranged from 64.0±13.0 to 70.8 ± 19.9 mg L^{-1} (Giao & Minh, 2021). The TSS in the canals in Hau Giang province were 32.8 ± 6.4 to 101.8 ± 40.9 mg L^{-1} (Giao, 2020); while the TSS ranged from 16-176 mg L^{-1} in the canals of Soc Trang province (Tuan *et al*., 2019). The TSS in coastal water bodies was much higher than in freshwater bodies, which is the result of boat operations, wastewater from aquaculture, agricultural production, and aquatic plant growth. In addition, eight out of the ten sampling locations had TSS values exceeding the permissible limits. This frequency of contamination showed that the values of TSS can increase other pollution problems such as pathogenic microorganisms, pesticides, and antibiotics, thereby increasing the negative impacts on humans and the environment (Mekong River Commission, 2015; Ministry of Natural Resources and Environment, 2015b).

The nitrite concentration ranged from 0.01 mg L^{-1} (BL8) to 0.23 mg L^{-1} (BL5) (**Table 3**). Only nitrite values at two locations, BL1 and BL8, were within the limits published in QCVN 08-MT:2015/BTNMT (column B1). Nitrite in the remaining locations exceeded QCVN 08-MT:2015/BTNMT by 1.2 to 4.7 times. In other water bodies, the nitrite concentration has been reported as 0.04 ± 0.017 mg L^{-1} in Hau Giang province (Giao, 2020) and 0.0 ± 0.0 to 0.2 ± 0.3 mg L^{-1} in the Tien River (Giao *et al*., 2021). The nitrite concentration in the study area was higher than that in previous studies. Nitrite-contaminated water is of great concern because it can cause serious diseases such as methemoglobinemia or blue skin.

Nitrate in the study area ranged from 0.68 mg L^{-1} (BL1) to 5.55 mg L^{-1} (BL10) (**Table 3**). At all the locations, nitrate was below the allowable limit of QCVN 08-MT:2015/BTNMT, column B1. According to the previous studies by Giang *et al.* (2020) and Giao *et al*. (2021), the nitrate concentrations in the My Thanh River (Soc Trang province) and Tien Giang province were 0.02-0.97 mg L^{-1} and 0.1 ± 0.1 to 0.4 ± 0.2 mg L^{-1}, respectively. Similar to nitrite, the nitrate concentrations in the studied areas were higher than in other places in the Mekong Delta. A suitable nitrate concentration for aquaculture ranges from 0.2 to 10.0 mg L^{-1} (Boyd, 1998). However, this range of nitrate concentrations could cause eutrophication.

Ammonium in the water bodies of the study area varied from 0.02 mg L^{-1} (BL10) to 1.25 mg L^{-1} (BL1) (**Table 3**). The ammonium nitrogen content at the locations BL1 and BL4 exceeded the allowable limit of QCVN 08-MT:2015/BTNMT (column B1) by 1.39 times and 1.32 times, respectively. Ammonium at the remaining locations was within the permissible limits. The N-NH_4^+ concentration in this study was higher than in Hau Giang province by 0.27 ± 0.16 mg L^{-1} (Giao, 2020) and in Tien Giang province by 0.3 ± 0.4 to 0.5 ± 0.5 mg L^{-1} (Giao *et al*., 2021). According to Boyd (1998), the N-NH_4^+ concentration in the water should not exceed 5.00 mg L^{-1} because it could cause eutrophication and toxicity for aquatic life through the use of nutrients by phytoplankton and result in a significant increase in the density of algae in the water. However, this process also depends on the pH, N-NH_4^+ concentration, and aquatic species types.

Orthophosphate ranged from 0.01 mg L^{-1} (BL4) to 0.32 mg L^{-1} (BL2) (**Table 3**). Dissolved phosphorus levels at the survey sites were within the allowable QCVN 08-MT:2015/BTNMT

(column B1), except for BL2. The current results showed that dissolved phosphorus in the study area was higher than in previous studies in freshwater bodies (Dinh Diep Anh Tuan *et al*., 2019; Giao & Minh, 2020; Giang *et al.*, 2020).

Iron in the studied water bodies ranged from 0.02 mg L^{-1} (BL10) to 1.25 mg L^{-1} (BL1) (**Table 3**), which were within the allowable limit of the regulation for surface water quality. Fe in the water bodies was 0.3-3.75 mg L^{-1} in Soc Trang province (Dinh Diep Anh Tuan *et al*., 2019), and 1.2 ± 0.6 mg L^{-1} in Hau Giang province (Giao, 2020). The content of Fe in the water bodies in this study and previous studies were all high since the Mekong Delta has large areas of acid sulfate soil that could release toxic metals such as Fe and Al.

Chloride in the surface water ranged from 397 mg L^{-1} (BL1) to 21,128 mg L^{-1} (BL6) (**Table 3**). Chloride concentrations at all the sampling locations exceeded the limit of QCVN 08-MT:2015/BTNMT, column B1, except for BL1. High chloride in surface water could be attributed to a decrease in freshwater flows associated with an increase in upstream exploitation and seawater intrusion (Shammi *et al.*, 2017). This means that coastal areas like Bac Lieu province are susceptible to saline water intrusion that contains high anions like chloride.

Coliform densities in the study area ranged from 2,100 to 9,500 MPN 100 mL^{-1} (**Table 3**). Coliform densities at two positions (i.e., BL1 and BL4) exceeded the limit value in the Vietnamese standards. In the other sites, coliforms were within the permissible level of B1 in QCVN 08-MT:2015/BTNMT. However, coliform density was much higher than the limit value in A1 of QCVN 08-MT:2015/BTNMT. Coliforms in the surface water of An Giang province (2,260-155,000 MPN 100 mL^{-1}) exceeded the permissible limit 2.14 to 7.02 times (Ly & Giao, 2018), and coliforms exceeded the limit from 1 to 36 times in the canals of Soc Trang province, ranging from 1,600-89,832 MPN 100 mL^{-1} (Dinh Diep Anh Tuan *et al*., 2019; Giang *et al.*, 2020). Coliforms probably originated from fecal materials (WHO, 2008). Coliform contamination is a common surface water problem in Vietnam (MRC, 2015; MONRE, 2015b).

Spatial variation of surface water quality in the dry season in Bac Lieu province

As can be seen in **Figure 2**, the ten monitoring sites were divided into three clusters at the Euclidean distance of 4. Cluster 1 was comprised of only BL1 in the Cai Day canal, Chau Hung town, Vinh Loi district, Bac Lieu province where the values of TSS, N-NH_4^+, Cl^-, and coliforms exceeded the limits of QCVN 08-MT:2015/BTNMT, column B1 (**Table 4**). Cluster 2 included the sampling sites BL4 and BL5 that are the Quan Lo Phung Hiep canal and Pho Sinh Canal, respectively, in Phuoc Long district, Bac Lieu province. This cluster was polluted with organic matter, nutrients, and salinity; of which, the values of BOD, COD, N-NH_4^+, and N-NO_2^- were high (**Table 4**). Cluster 3 included the sampling locations BL2, BL3, BL6, BL7, BL8, BL9, and BL10, which were heavily contaminated by parameters such as BOD, COD, TSS, N-NO_2^-, and Cl^- (**Table 4**). The water quality factors distinguishing each cluster were BOD, COD, TSS, N-NH_4^+, N-NO_2^-, Cl^-, and coliforms.

Identification of potential polluting sources of surface water quality

The PCA presented that 99.2% of the variation of the parameters in the study area was explained by 6 PCs (**Table 5**). PC1, PC2, and PC3 explained the water quality variance by 55.2%, 15.8%, and 13.5%, respectively. PC4, PC5, and PC6 only explained a total of 14.7% of the change in water quality in the study area. Based on the eigenvalue coefficient, the three main potential sources of water pollution were PC1, PC2, and PC3 because the coefficients were greater than 1 (Howladar *et al*., 2021) (**Figure 3**). This was because the component scores would have negative reliability once the coefficient was less than 1 (Cliff, 1988). Eigenvalues are the coefficients related to eigenvectors, which provide the amount of variance in each principal component. The larger value of these coefficients, the more significant the principal components are in the explanation of the variation of the data set (Groth *et al.*, 2013).

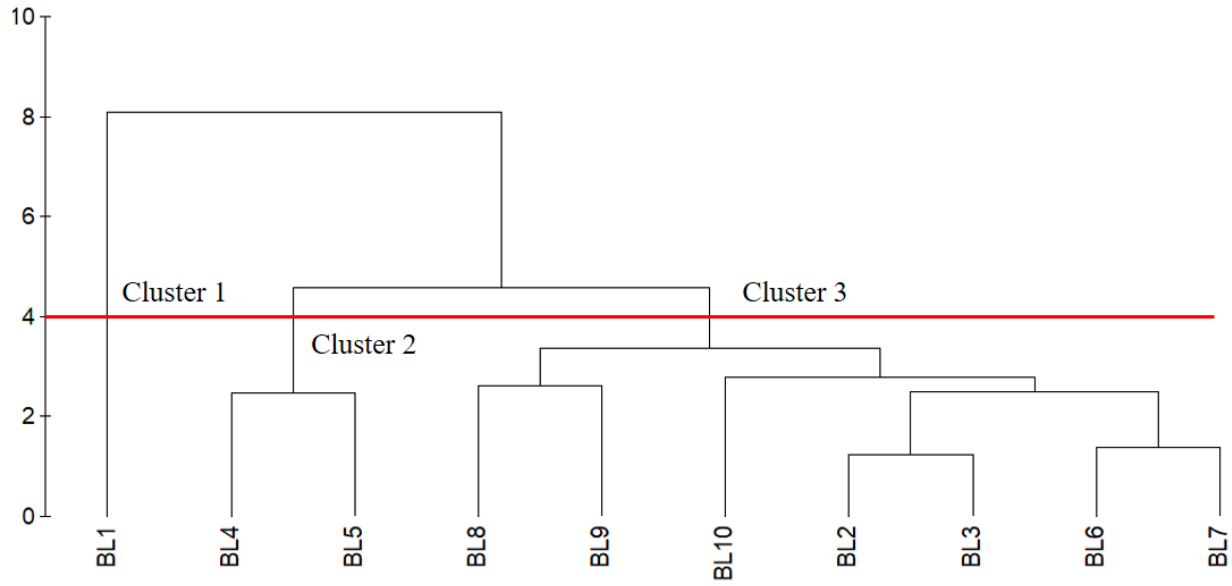

Figure 2. Clustering by surface water quality in the 2020 dry season in Bac Lieu province

Table 4. Characteristics of surface water quality of the three clusters in Bac Lieu province in the 2020 dry season

Variables	Cluster 1	Cluster 2	Cluster 3	Limit values*
pH	7.12	7.25	7.94	5.5-9
DO	5.14	5.38	4.60	≥ 4
COD	21.3	266.5	480.0	30
BOD	13.8	179.5	321.7	15
TSS	68.0	29.0	189.2	50
$N\text{-}NO_2^-$	0.02	0.18	0.08	0.05
$N\text{-}NO_3^-$	0.68	2.67	4.12	10
$P\text{-}PO_4^{3-}$	0.02	0.01	0.23	0.3
$N\text{-}NH_4^+$	1.25	0.92	0.29	0.9
Fe	0.38	0.18	1.11	1.5
Cl^-	397	19,568	19,375	350
Coliforms	9,500	6,850	3,243	7500

*Note: * Limited values in column B1 of National Technical Regulation on Surface Water Quality (QCVN 08-MT: 2015/BTNMT)*

The important water parameters were identified using the weighted correlation coefficient of each PC. This coefficient indicated the correlation between the water quality variables and the potential polluting sources, thus becoming the main factors influencing water quality. The weighted correlation coefficient was assessed as strong, moderate, and weak if the absolute value was greater than 0.75, between 0.75-0.50, and between 0.50-0.30, respectively (Chounlamany *et al.*, 2017). PC1 was weakly correlated with pH (-0.31), BOD (-0.36), COD (-0.36), $P\text{-}PO_4^{3-}$(-0.33), and coliform (0.36) (**Table 5**). This PC was related to the wastes from human activities such as effluents from domestic and industrial discharges, agricultural runoff, sewage wastes, and wastewater treatment plants that release organic matter and nutrients (Phung *et al.*, 2015). PC2 was also weakly correlated with pH (-0.350) and $N\text{-}NO_3^-$ (-0.32), and

Table 5. Key water variables affecting surface water quality in Bac Lieu province in the 2020 dry season

Variables	PC1	PC2	PC3	PC4	PC5	PC6
pH	-0.31	-0.35	0.21	-0.02	-0.33	0.09
DO	0.28	0.10	0.45	-0.34	0.10	-0.14
COD	-0.36	0.26	-0.05	0.12	-0.00	-0.01
BOD	-0.36	0.26	-0.06	0.09	0.00	0.07
TSS	-0.19	0.28	-0.40	-0.50	0.49	-0.25
$N\text{-}NO_2^-$	0.04	0.57	0.45	-0.19	-0.15	0.19
$N\text{-}NO_3^-$	-0.27	-0.32	0.21	0.14	0.61	0.20
$P\text{-}PO_4^{3-}$	-0.33	0.12	-0.31	0.08	-0.27	0.16
$N\text{-}NH_4^+$	0.29	0.26	-0.29	-0.65	-0.00	0.65
Fe	-0.25	-0.26	0.06	0.32	-0.07	0.50
Cl^-	-0.27	0.25	0.39	0.13	0.28	0.16
Coliforms	0.36	-0.12	-0.10	0.13	0.31	0.33

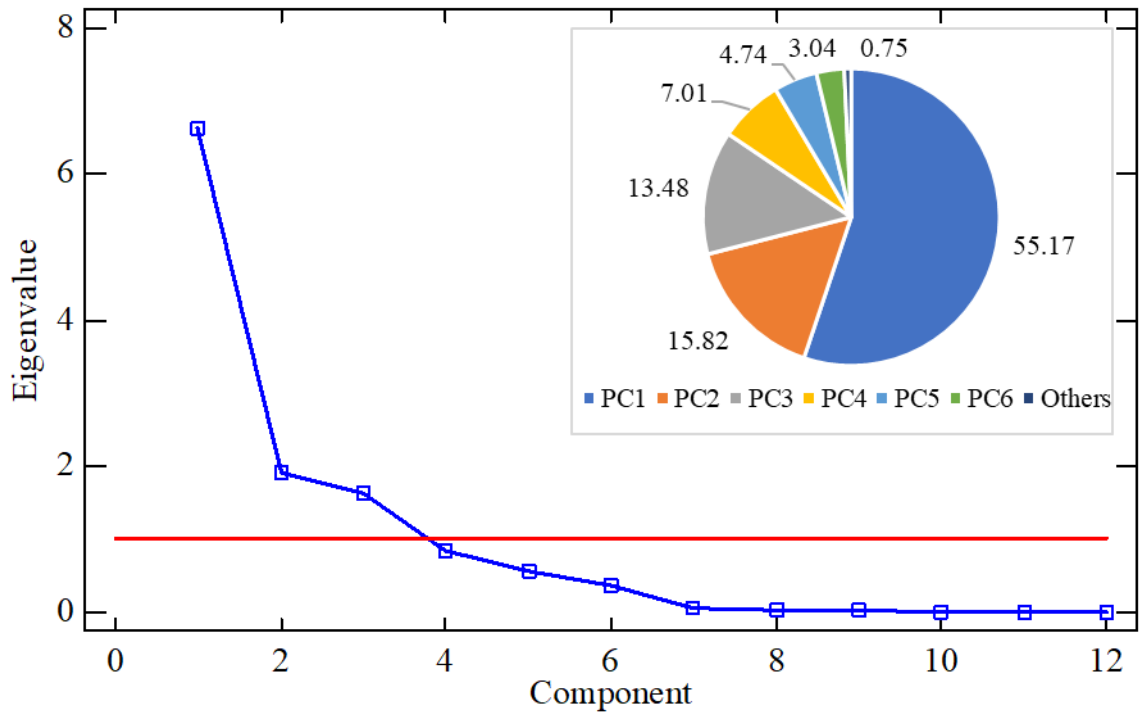

Figure 3. The eigenvalues of each principal component

moderately correlated with $N\text{-}NO_2^-$ (0.57). This source of water pollution was related to nitrogen species conversion, which depends on nitrogen concentrations and dissolved oxygen. This source was from hydrological factors and human activities that release nitrogen species (Giao *et al*., 2021a). PC3 was weakly correlated with DO (-0.40), $N\text{-}NO_2^-$ (0.45), $P\text{-}PO_4^{3-}$ (-0.31), and Cl^- (0.39). PC3 was related to natural conditions and human activities. The DO, TSS, and Fe parameters were weakly correlated with PC4, while $N\text{-}NH_4^+$ moderately contributed to PC4. PC4 could be from natural conditions, runoff, and human activities. PC5 was moderately correlated to $N\text{-}NO_3^-$, while weakly correlated to pH, TSS, and coliforms. This pollution could be from both natural and human activities. PC6 was moderately correlated with $N\text{-}NH_4^+$ and Fe,

while it was weakly correlated with coliform. PC6 could be from both natural and human causes.

It was found that pH was influenced by PC1, PC2, and PC5; DO was impacted by PC3 and PC4; TSS was weakly correlated with PC3, PC4, and PC5; $N\text{-}NO_2^-$ was modified with PC2 and PC3; $N\text{-}NO_3^-$ was controlled by PC2, and correlated with PC5; $P\text{-}PO_4^{3-}$ was weakly influenced by PC1 and PC3; $N\text{-}NH_4^+$ was related to PC4 and PC6; Fe was affected by PC3; coliform was associated with PC1, PC5, and PC6; and Cl^- was only influenced by PC3. Water quality in Bac Lieu province was complicatedly impacted by several factors such as natural causes (runoff, hydrology, and acid sulfate soil) and human activities (transport, agriculture, aquaculture, and daily activities). The parameters of pH, TSS, DO, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, coliforms, and Cl^- had the main influences on the variation of surface water quality in the dry season in the water bodies in Bac Lieu province. Therefore, these variables need to be included in the monitoring tasks.

Conclusions

Surface water in this study area was contaminated; the mean values of TSS, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $P\text{-}PO_4^{3-}$, salinity, and coliforms all exceeded the limits of QCVN 08-MT:2015/BTNMT, column B1. The PCA presented that six PCs explained 99.2% of the variation of the parameters in which PC1, PC2, and PC3 were the main potential water pollution sources. The key variables on surface water quality in the dry season were pH, TSS, DO, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, coliforms, and Cl^-. These variables should be included in the monitoring tasks in the future. The CA presented that water quality in the dry season was classified into three clusters based on BOD, COD, TSS, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, coliforms, and salinity. The quality of surface water in the study area could be influenced by runoff, riverbank erosion, and wastewater from domestic activities, urban areas, industrial areas, and agricultural zones. Future studies should focus on investigating specific sources of water pollution for appropriate response measures.

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