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Application of GIS and Multi-Criteria Statistical Techniques in Assessing Water Quality in the Coastal Province of Vietnamese Mekong Delta

Nguyen Thanh Giao*, Huynh Thi Hong Nhien

College of Environment and Natural Resources, Can Tho University, Vietnam
* Corresponding author: ntgiao@ctu.edu.vn

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Abstract

The study was conducted to evaluate the quality and spatial distribution of surface water quality in Soc Trang, a coastal province using Geographic information system (GIS) and multivariate statistical analysis. Water monitoring data was collected from 19 sampling locations with 19 parameters were analyzed from February 2019 to August 2020. The results indicated that water quality was contaminated with organic matters, nutrients, coliforms and salinity. Water quality index (WQI=22–73) indicated that water quality was from poor to medium level. Cluster analysis (CA) classified 19 monitoring sites into 7 groups and 19 months into 3 seasons including rainy season, rainy season-early dry season, dry season-early rainy season. CA results showed that the location and frequency of water quality monitoring could be significantly reduced, saving up to 75% the monitoring costs. The maps of the polluted parameters (TSS, DO, BOD, COD, TOC, NH_4^+-N, NO_2^--N, Coliform, Fe, Cl^-) illustrated that the areas located in the interior fields and near the sea had poorer water quality compared to the areas adjacent to the Hau River. The combination of multivariable statistics and GIS was very useful for spatial and temporal analysis of water quality monitoring data.

Keywords: Cluster analysis; Coliform; GIS; Organic pollution; Soc Trang Province

Introduction

Water quality management is highly prioritized in the world in terms of policy, management, and planning [1]. Surface water resource is unevenly distributed and highly spatially and temporally fluctuated. For example, the amount of fresh surface water is abundant in the inland provinces but is relatively rare in the coastal areas. The growth of population, economic development, and urbanization are polluting surface water making it rarer. The problem of water use competition may become more seriously in the near future. Vietnamese Mekong Delta River is at risk of water pollution and water shortage, especially in the context of the normal flow of the Mekong River is being

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altered due to upstream construction of dams and other uses and activities [2]. The amount of surface water and the level of water quality for social and economic activities in the Vietnamese Mekong Delta have become challenging. Soc Trang is a coastal province in the Vietnamese Mekong Delta, located in the south of the estuarine area of Hau River. Its terrain is relatively low and flat with several different natural ecological zones characterized by surface freshwater, brackish water, saline water which facilitate the diversification of aquacultural and agricultural production in addition to the industrial, tourism and service activities [3]. In relation to surface water quality in this coastal province, the saline water intrusion has significant effect on quality and quantity of the water resources especially in the dry season resulting in various obstacles for life of the people in the province [4–5]. Several pollution sources from agricultural and aquacultural production, industrial, tourism and service as well as daily life activity have additionally discharged wastes into the rivers and canals in the province [5]. Surface water quality is becoming shortage and polluted and groundwater is also polluted and limited in reserves [6]. Assessing and managing surface water quality become very crucial in the coastal area in Soc Trang Province.

Monitoring surface water quality is an essential task. A water quality monitoring network includes the design of the monitoring site, determination of sampling frequency, selection of analytical parameters, and evaluation methods. Water quality monitoring network in Vietnam have been implementing for 10 years focusing on limited sites, frequency and water quality parameters due to budget constraint. The data of water quality variable are mainly compared to national technical regulation on surface water quality standard (QCVN 08-MT:2015/BTNMT) and water quality index (WQI). Recently, several advanced techniques have been used for designing and evaluating data of surface water monitoring data. Several scientists have applied multivariate statistical techniques for assessment of water quality of multi-site and multi-parameter water quality datasets [7–9]. In which, Cluster Analysis (CA) and Principal Component Analysis (PCA) were widely and effectively used to evaluate spatial and temporal variation as well as the main water quality parameters affecting water quality [10–12]. The use of CA and PCA could help in optimizing sampling location, frequency of sampling time and predicting of polluting sources. In addition, some researchers have used geographic information systems (GIS) to analyse and present large amounts of spatial data of water quality [13–14]. Additionally, changes in the spatial distribution of the monitoring locations, and zoning water quality, sources of pollution could be visually presented by the application of GIS [15–16]. This study aimed to use both multivariate statistical analysis and GIS in the analysis of surface water quality in Soc Trang Province using the most recent water quality monitoring data. The results of the present study could provide additional tools for Vietnamese environmental managers in reconsidering monitoring network and better interpretating surface water quality data.

Materials and methods

1) Description of sampling locations

Soc Trang Province is located at the estuarine of the Hau River and bordered to the East Sea with the length of the coast of 72 km. The water resource in the canal and river systems in Soc Trang Province is affected by local rainfall (1,660 – 2,230 mm a^{-1}), flow from upstream of Hau River and seawater. For example, the tide has caused salinity intrusion in the dry season, as the amount of freshwater flowing in from the upstream decreases, and the local evaporation rate increases. The major land uses in the study area are agricultural cultivation and aquaculture. Surface water samples were collected on the main rivers and canals representing water quality in Soc Trang Province including Hau River, My Thanh River, Quan Lo-Phung Hiep Canal, Nhu Gia River, Soc Trang-Phung Hiep Canal, Thanh Tri – Nga Nam Canal, Du Tho River and Dinh River (Figure 1). Detail of the site description was presented in the Supplementary Material (SM) 1.

2) Water sample collection and analysis

Water sampling was implemented from February 2019 to August 2020 at 19 monitoring points as indicated in Figure 1. The water samples were collected once a month at low and high tides since the hydrological regime in Soc Trang Province is influenced by semi-tidal. Surface water samples were collected and stored according to the instructions in TCVN 6663-6: 2018 – Guidance on water sampling of rivers and streams [17], TCVN 6663-3: 2016 - Guidance on preservation and handling of water samples by Vietnam Environment Administration (2016) [18]. Water sampling was performed at depth of 30–50 cm, in the middle of the canals and rivers. Before the sampling, the water sample containers were rinsed three times using the field water. For microbiological samples, the containers were sterilized before use to avoid contamination.

Five groups of water quality parameters were selected based on natural conditions and the socio-economic activities in the study area. Firstly, the water variables representing organic and nutrient pollution were total suspended solids (TSS, mg L^{-1}), dissolved oxygen (DO, mg L^{-1}), biological oxygen demand (BOD, mg L^{-1}), chemical oxygen demand (COD, mg L^{-1}), total organic carbon (TOC, mg L^{-1}), nitrite (NO_2^--N, mg L^{-1}), nitrate (NO_3^--N, mg L^{-1}), ammonium (NH_4^+-N, mg L^{-1}), orthophosphate (PO_4^{3-}-P, mg L^{-1}), total nitrogen (TN, mg L^{-1}) and total phosphorus (TP, mg L^{-1}). Secondly, water quality parameters reflecting physical and chemical characteristics included turbidity (NTU), pH; temperature (T, ^{0}C), sulfate (SO_4^{2-}, mg L^{-1}). Thirdly, the water salinity indicators comprised electrical conductivity (EC, mS cm^{-1}) and chloride (Cl^-, mg L^{-1}). Next, the water parameter showing microbiological pollution was coliform (MPN 100 mL^{-1}). Lastly, heavy metal in water was indicated by iron (Fe, mg L^{-1}). The water quality parameters including temperature, pH, turbidity, conductivity and dissolved oxygen were directly measured at the field while the remaining parameters were determined in the laboratory according to the methods of APHA (1998) [19].

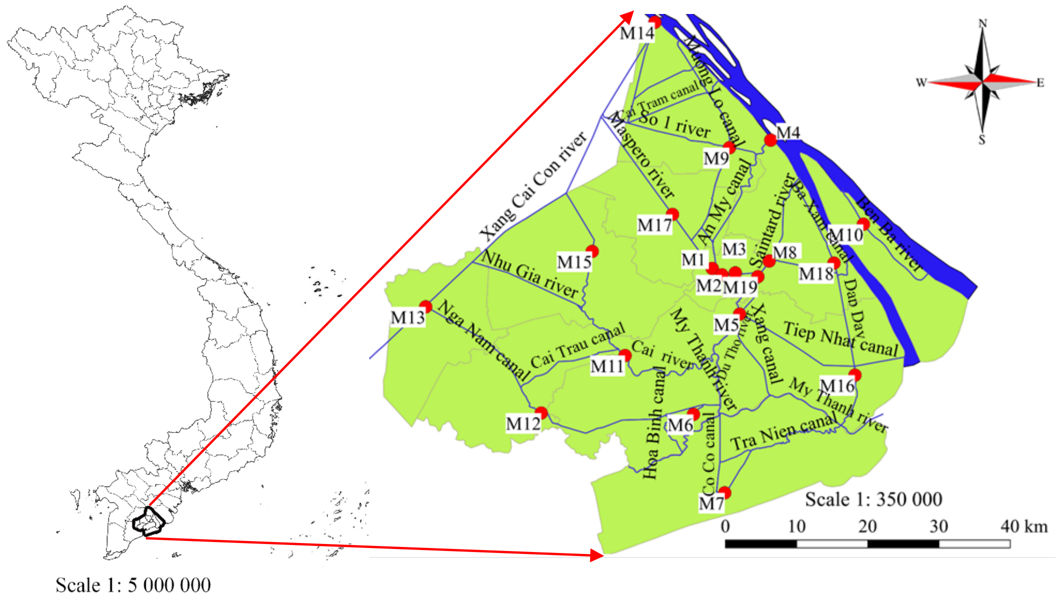

Figure 1 Map of the sampling locations.

3) Data analysis

The water quality index was used to calculate the overall water quality through physicochemical and biological parameters. Applying the calculation method of the water quality index (WQI) based on the Decision No. 1460/QD-TCMT dated 12/11/2019 of the Vietnam Environment Administration (2019) [20], the calculation parameters of WQIVN were divided into 3 groups including pH parameters (Group I), organic and nutritional parameters (Group II – DO, BOD, COD, TOC, NH_4^+- N, NO_2^--N, NO_3^--N, PO_4^{3-}-P) and microbiological parameter (Group III – Coliform). After calculating the WQI for each parameter in the groups, the water quality index was calculated by the Eq. 1.

The analysis and presentation of spatial and temporal data were performed using the CA and PCA combined with GIS. CA was a method of grouping objects (location/time) into groups/ clusters based on the similarities and differences of the objects to be analyzed [8, 11–12, 21]. Values commonly used to assess the degree of similarity include the values/concentrations of environmental quality assessment parameters. In this study, CA analysis was applied to evaluate the similarity/homogeneity of spatial/ temporal based on the mean values of 19 water quality parameters at locations/months. Euclidean distance and Ward algorithm were performed in cluster analysis [22]. PCA is used to extract important information from the original dataset. Each of the original variables is classified as one principal component (PC) and each PCs is a linear combination of the original variables [23]. The purpose of the PCA is to reduce the initial variables that do not contribute significantly to data variability. The correlation between PCs and original variables were exhibited by weighing factors (loading) [23]. The absolute values of weighing factors (WF) have a strong correlation between PCs and parameters when WF > 0.75, average correlation when 0.75 > WF > 0.5 and weak correlation when 0.5 > WF > 0.3 [24]. In this study, the PCA was used to predict some of the major pollution sources and to extract pollution parameters. Both CA and PCA analyses were computed using the copyrighted software Primer 5.2 for Windows (PRIMER-E Ltd, Plymouth, UK). In addition, GIS was used as a tool to assist in analyzing/ presenting spatial information of pollution parameters at the study sites. The sampling locations were geotagged using the GPS Garmin Etrex Touch 25 device. The values for each pollution parameter and the location coordinates were added as points and the object classification technique according to the value limits (graduated) was applied to represent pollution levels. In this research, QGIS software version 2.18.28 was used to build the thematic maps of the water pollutants.

$$WQI_{VN} = \frac{WQI_I}{100} \times \left(\frac{1}{k}\sum_{i=1}^{k} WQI_{II} \times WQI_{III}\right)^{1/2} \quad \text{(Eq. 1)}$$

where

WQ_{II}: The results of the calculation for parameters in group I

WQ_{III}: The results of the calculation for parameters in group II

WQ_{IIII}: The results of the calculation for parameter in group III

The WQI_{VN} results were compared with SM 2 to classify water quality and suitability for each purpose.

Results and discussion

1) Summary of water quality in the water bodies in Soc Trang Province

1.1) Frequency of pollution parameters

Each water quality parameter was considered polluted when it exceeds the water quality standards regulated in the National Technical Regulation on surface water quality (QCVN 08-MT:2015/BTNMT) [25–26]. The frequency of the polluting parameters was calculated by counting the number of times that such the parameters exceeded the permitted limits. The present study examined 15 water quality variables including temperature, pH, DO, BOD, COD, TOC, TSS, NH_4^+-N, NO_2^--N, NO_3^--N, TN, $PO_4{3^-}$-P, Cl^-, Fe and coliform since these parameters are currently regulated in QCVN 08-MT:2015/BTNMT. The frequency of the water pollutants at the study area was presented in Figure 2.

As can be seen from the Figure 2 that there were 12 out of 15 water quality parameters exceeded the regulation limits. The number of water variables exceeded the thresholds at each sampling site was from 6 to 12 parameters. All monitoring sites were contaminated with total suspended solids, organic matters, coliform, and iron. The frequency of the pollution parameters at M4, M9, and M14 had a tendency to be lower than the other locations (Figure 2). Water quality at these sites was not contaminated by nutrients (NH_4^+- N, NO_2^--N, NO_3^--N, PO_4^{3-}-P) and chloride. This could be because these locations are adjacent to Hau River and the large water flow from Hau River to M4, M9 and M14 could help in diluting certain sources pollutants discharging to these sites. In addition, these locations are far from the city and the sea, so the water source is less affected by urban activities and saltwater intrusion. This may indicate that socio-economic activities at the site have a direct influence on the water quality of a water body. A detailed information of causes of water quality variations was discussed in Section 3 in this study.

Sites	Temp	pH	TSS	DO	BOD	COD	TOC	NH_4^+-N	NO_2^--N	NO_3^--N	TN	$PO_4^{3-}-P$	Cl^-	Fe	Coliforms
M19	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1
M18	0	0	1	1	1	1	1	0	1	0	0	0	1	1	1
M17	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1
M16	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1
M15	0	0	1	1	1	1	1	1	1	0	0	0	0	1	1
M14	0	0	1	1	1	1	1	0	0	0	0	0	0	1	1
M13	0	0	1	1	1	1	1	1	1	0	0	0	0	1	1
M12	0	0	1	1	1	1	1	1	0	0	1	0	0	1	1
M11	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1
M10	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1
M9	0	0	1	1	1	1	1	0	0	0	0	0	0	1	1
M8	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1
M7	0	0	1	1	1	1	1	1	1	0	1	0	1	1	1
M6	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1
M5	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1
M4	0	0	1	1	0	1	1	0	0	0	0	0	1	1	1
M3	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1
M2	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1
M1	0	0	1	1	1	1	1	1	1	0	1	1	1	1	1

Parameters

Figure 2 Frequency of the water pollutant at the sampling locations.
Remark: "1" was the value over the specified limit (called a failed parameter for DO).
"0" was the value within the specified limit.

With regard to the temporal analysis, the present study showed that 13 out of 15 water quality parameters resulted in water problems. Every month, there were from 9 to 13 water quality variables exceeded the threshold values in QCVN 08-MT:2015/BTNMT (Figure 3). As can be seen that the numbers of polluting parameters in 2019 in the months of T2_19, T3_19, and T4_19 (9 parameters) were lower than those in the months of T6_19, T7_19, and T8_19 (11 – 12 parameters). This water pollution tendency was found to be similar at the study area in 2020. The water quality was well related to the hydrological changes including tidal regime and rainfall. The hydrology in Soc Trang Province is influenced by the irregular semi-diurnal tidal regime. The average water level deviation was insignificant from 22.25 to 26.92 cm month^{-1}. The highest tidal peak was 160 cm (in October, November), the lowest was 123 cm (in May, August), the highest tidal base was -24 cm (November), the lowest was -103 cm (June), the average tidal ranged from 194 to 220 cm. Former study by Tung and Thinh (2014) [27] reported that the rainfall in Soc Trang Province was highest in September and October (307.70–504.10 mm month^{-1}). The present study found that the water level on the river and the rainfall were high, the number of the water polluting parameters was low. In contrast, the water level on the river and the rainfall were low, the number of the water polluting variables was high.

Overall, the water quality in canals/rivers in Soc Trang Province in 2020 tended to decrease comparing to that in 2019 indicated by an increase in the frequency of the water polluting parameters in 2020. In other words, the frequency of the water polluting parameters has increased over the study period (2/2019 - 8/2020). The results indicated that the quality of the water environment has been deteriorated. This could be because wastes have been improperly and inefficiently treated before dischared to the receiving water. Surface water quality management strategy should be carefully reconsidered to improve surface water quality in Soc Trang Province.

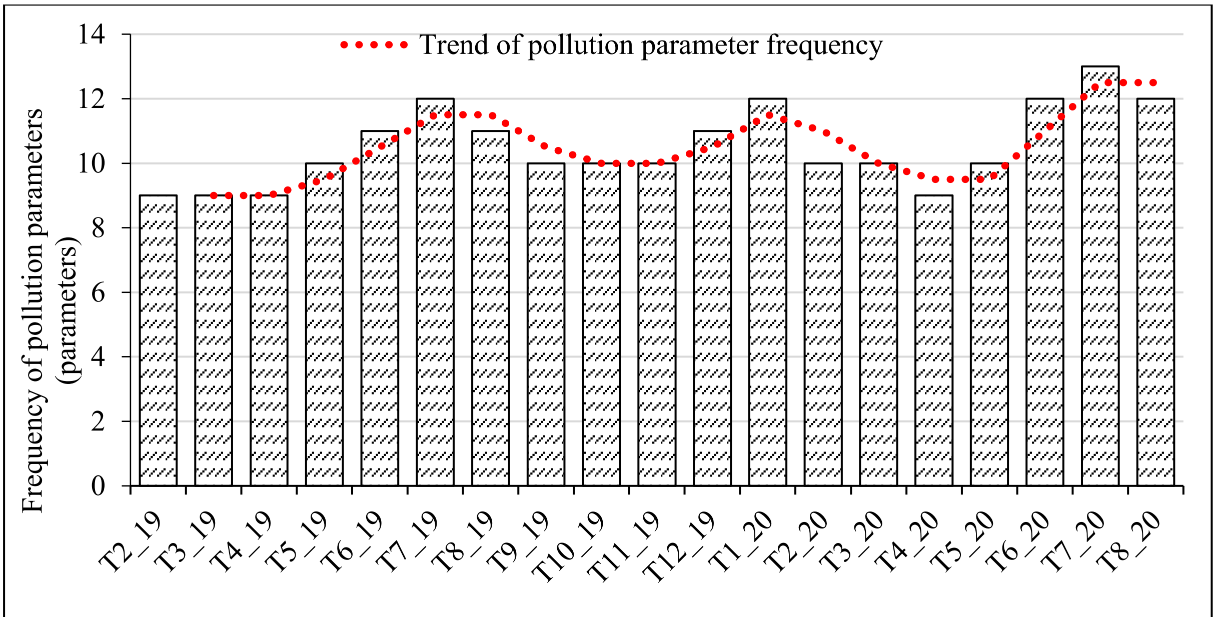

Figure 3 Frequency of pollution parameters in the monitoring period.
Remark: T1_19 indicates the month of January in 2019 and T12_20 indicates December in 2020.

1.2) Water quality index (WQI)

According to Decision 1460/QD-TCMT dated 12/11/2019 of the Vietnam Environment Administration (2019) [20], ten parameters were used to calculate the water quality index (WQI) for 19 locations for an overall assessment of water quality in Soc Trang Province. The calculation results showed that only one position (M6) was classified as average (WQI = 73), 12/ 19 positions (WQI = 26 – 30) and 6/19 positions (WQI = 22 – 25) were found to be fair and poor water quality, respectively. Coliform (5,374 MPN 100 mL^{-1}) was the main factor resulting in significant difference in water quality at the location M6 and the other locations. As previously discussed, there was less frequency of the water polluting parameters at the site M6 (6–8 parameters) involved in the process of WQI calculation. This was found similar for the location M4, M9 and M14. Therefore, the numbers of water quality parameters that exceeded the standards would determine the water quality levels classified by WQIVN. Our observations showed that the three water quality parameters including DO, COD, and coliforms were the most influencing on water quality index calculation for the rivers/canals in Soc Trang Province. The water quality at the locations M1, M2, M3, M7, M11, and M17 were heavily polluted classified by WQIVN (Figure 4). Water quality tended to be more polluted in central areas of Soc Trang Province, where commercial services, urban areas and industrial zones were concentrated; especially at positions M1, M2, M3 where festivals and markets often take place. In short, the water quality in the study area is classified not suitable for domestic activities and water supply. Appropriate treatment measures are urgently needed.

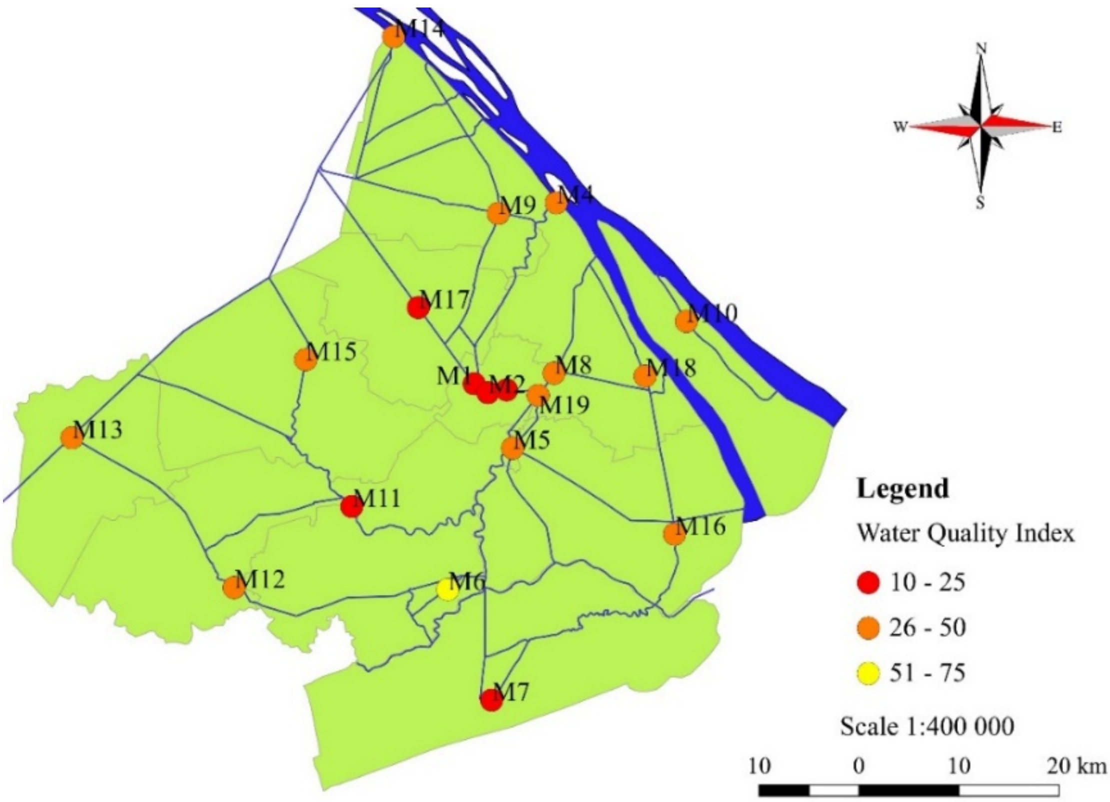

Figure 4 Spatial distribution of average water quality based on water quality index.

2) Spatial and temporal variation of water quality

CA analysis has placed each monitoring position in a certain cluster based on the analysis of 19 parameters and the squared Euclidean distance between each position and the cluster centroid. Seven clusters were established using cluster analysis for 19 monitoring locations (Figure 5). Cluster 1, Cluster 2, Cluster 3, Cluster 4, and Cluster 5 consist only of one location per cluster, including M9, M10, M2, M3, and M13, repspectively. Cluster 6 included the 11 locations of M1, M4, M5, M6, M8, M11, M14, M15, M16, M18, and M19 (Figure 5). Cluster 7 comprised the sites M7, M12, and M17. The similarity of water quality characteristics at the locations in the Cluster 6 and Cluster 7 could be utilized to reduce the sampling location thus reducing monitoring cost. The water quality parameters resulting in different water quality in each cluster were presented in Table 1.

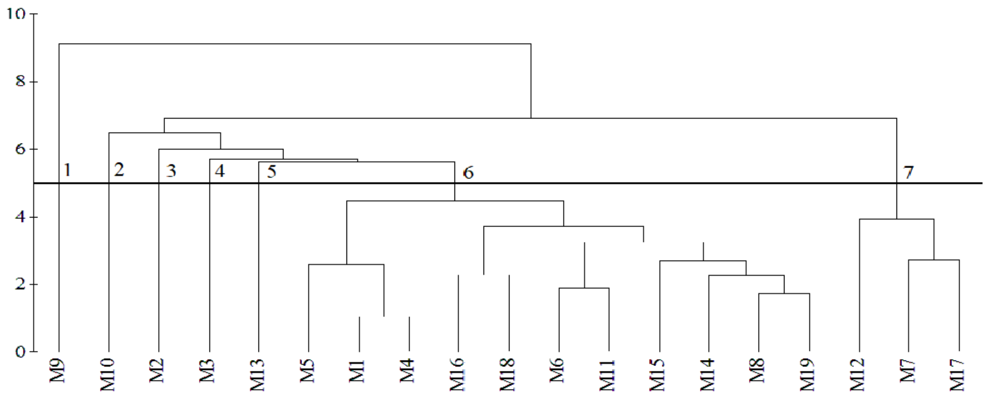

Figure 5 Spatial variation of water quality in Soc Trang Province 2019–2020.

Table 1 Mean of the water quality parameters for spatial variation of water quality in 2019–2020

Parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	QCVN 08-MT
	Number of sampling sites in cluster							
	1	1	1	1	1	11	3	
Temp	29.22	29.92	28.76	29.15	29.32	29.40	29.48	-
pH	7.17	7.00	7.10	7.12	7.03	7.15	7.13	6.5 - 8.5
DO	3.60	3.59	2.46	2.86	2.84	3.11	2.66	≥ 6
EC	109.65	646.43	159.89	220.46	80.44	313.40	431.61	-
Turbidity	93.23	91.01	58.56	70.50	74.69	77.22	68.31	-
BOD	4.47	6.25	8.94	6.62	5.25	5.80	6.93	4
COD	21.64	29.43	32.35	28.98	23.43	26.83	32.96	10
TOC	5.59	7.59	11.05	10.05	8.93	8.49	11.60	4
TSS	95.66	103.20	51.31	80.26	71.38	83.68	70.72	20
NH_4^+-N	0.15	0.40	2.70	1.04	0.49	0.52	1.03	0.3
NO_2^--N	0.05	0.08	0.10	0.16	0.08	0.08	0.08	0.05
NO_3^--N	0.53	0.53	0.23	0.37	0.26	0.33	0.24	2
TN	1.83	2.44	4.58	2.94	1.95	2.41	3.18	-
PO_4^{3-}-P	0.06	0.03	0.53	0.17	0.05	0.12	0.11	0.1
TP	0.37	0.31	0.93	0.58	0.31	0.42	0.47	-
Cl^-	248.46	1,938.67	396.00	595.50	187.78	937.95	1524.10	250
SO_4^{2-}	61.09	306.44	58.22	119.18	50.79	143.99	206.46	-
Fe	1.41	1.55	1.42	1.84	1.71	1.62	1.56	0.5
Coliform	47,770	32,770	70,010	107,105	21,775	38,980	69,515	2,500

Generally, the mean values of the water quality parameters in Cluster 1, Cluster 5, and Cluster 6 were lower than those in the remaining clusters (Cluster 2, 3, 4, and 7) (Table 1). The values of EC, chloride, and TSS were the highest in cluster 2, which represented salinity and suspended solids pollution; while most parameters indicating nutrient and organic pollution were the highest in cluster 3. The highest mean values of NO_2^--N, Fe, and coliform were found in Cluster 4. COD, TOC, and SO_4^{2-} were found high at all clusters which could be the representative of the overall effects of aquacultural activities [28].

CA analysis has divided 19 months of the sampling frequency into three clusters, namely Cluster 1, 2, and 3 (Figure 6). Cluster 1 was formed from 4 months and all the monitoring months in this cluster were in the rainy season in 2019 (T7_19, T9_19, T10_19 and T11_19). Cluster 2 was the 9 monitoring months including 6 months in the rainy season (T5_19, T6_19, T8_19, T12_19, T7_20, and T8_20) and 3 months in the dry season (T2_19, T1_20, and T3_20). This cluster was dominated by the months in the rainy season. Moreover, the similarity in water quality in 2019 and 2020 was also noted in the study, specifically in February 2019 (T2_2019) and June 2019 (T6_2019) the water quality was almost similar to that of January 2020 (T1_20) and July 2020 (T7_20), respectively. Meanwhile, Cluster 3 was formed from 6 months (T3_19, T4_19, T2_20, T4_20, T5_20, and T6_20), and these months represented mid-end of the dry season and onset of the rainy season; dominated by the months of the dry season. From this analysis, it can be seen that the sampling frequency in the study area may only need to be done 3 times per year. Specifically, the months in each time can be selected as follows Period 1 (December, January, February, March), Period 2 (April, May, June) and Period 3 (July, August, September, October, November). This reduction could help in saving approximate 75% of the monitoring costs during the year. The previous research by Giao (2020) [29] also reported that sampling frequency could be reduced from 12 months to 3–4 months in the case of water monitoring in water bodies in An Giang Province. These clusters represented water quality at a certain temporal [30] and average values of water quality parameters in 3 clusters were detailed in Table 2. Water quality in Cluster 1 was polluted by organic matter (BOD, COD, and TOC), nutrients (NH_4^+-N, NO_3^--N, PO_4^{3-}-P, and TP), and microorganism (coliform). The increase in pollutants of the months in cluster 1 compared to the other clusters can be attributed to the process of the leaching pollutants from the soil surface, agricultural overflows; because the rainfall is often concentrated in the months included in cluster 1. Similarly, cluster 2 tended to be similar to cluster 1; nevertheless, the pollution level was lower; this can be explained by the fact that low rainfall at the beginning of the rainy season resulted in less pollutants washout [31]. In addition, the rainy season in the Mekong Delta is usually late in recent years. The leaching and dilution of pollutants in the water at the end of the rainy season may have partially improved water quality in the early of the dry season. Meanwhile, Cluster 3 showed that the water quality tended to be salty and high in dissolved ions since chloride, pH and EC were the highest; this has been also reported in the previous studies [3, 26]. Soc Trang Province has low terrain and close to the sea - which was a favorable condition for the saline intrusion to occur easily in the dry season, which can be considered as the cause of high Cl^- and EC concentrations in cluster 3. According to the sea level rise scenario, Soc Trang will be one of 10 provinces in the Mekong Delta that will be seriously affected by saline intrusion in the future [32–33]. Furthermore, water pollution by SO_4^{2-} was also the highest in cluster 3; this could lead to adverse effect on agricultural cultivation.

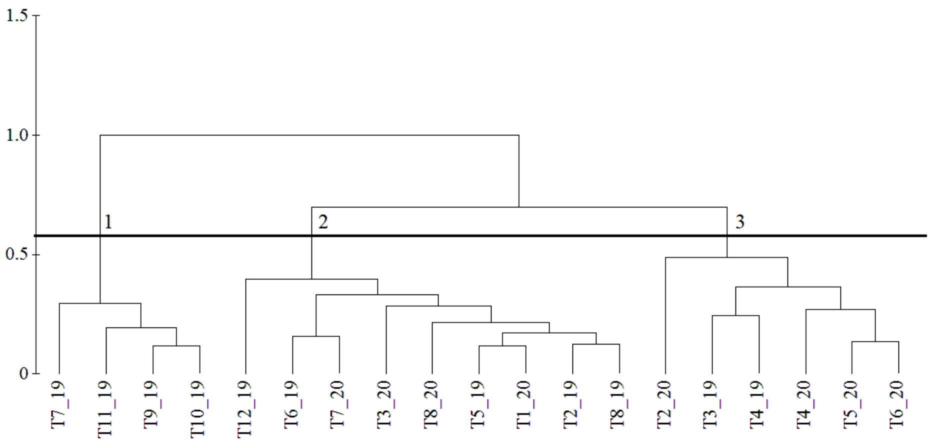

Figure 6 Temporal variation of water quality in Soc Trang Province 2019–2020.

Table 2 Mean of the water quality parameters in the temporal analysis

Parameter	Cluster 1 (Rainy season)	Cluster 2 (Dominated by months in the rainy season)	Cluster 3 (Dominated by months in the dry season)	QCVN 08-MT
Temp	29.15±0.87	29.08±1.3	30.02±1.37	-
pH	7.14±0.11	7.14±0.43	7.23±0.38	6.5 - 8.5
DO	2.78±0.42	2.97±0.23	3.26±0.18	≥ 6
EC	81.88±32.04	309.82±189.03	476.36±248.8	-
Turbidity	101.21±38.67	72.45±12.07	65.7±7.19	-
BOD	6.82±1.55	5.8±0.86	6.22±0.72	4
COD	29.78±3.13	26.03±3.97	29.28±6.61	10
TOC	11.71±1.96	9.02±1.98	7.31±1.09	4
TSS	99.12±37.46	73.96±13.41	81.51±13	20
NH_4^+-N	0.87±0.25	0.69±0.35	0.58±0.36	0.3
NO_2^--N	0.07±0.01	0.09±0.04	0.08±0.06	0.05
NO_3^--N	0.38±0.09	0.31±0.09	0.35±0.25	2
TN	2.74±0.69	2.76±0.94	2.19±0.71	-
PO_4^{3-}-P	0.16±0.02	0.13±0.06	0.1±0.03	0.1
TP	0.59±0.16	0.43±0.09	0.36±0.08	-
Cl^-	167.81±89.86	860.27±551.45	1669.82±722.22	250
SO_4^{2-}	45.9±29.89	134.15±80.03	233.48±101.68	-
Fe	2.51±0.83	1.45±0.2	1.24±0.17	0.5
Coliforms	98614.47±19969	45792.05±21638	22091.49±10192.53	2,500

3) Spatial distribution of key water pollution parameters in the water bodies in Soc Trang Province

Human activities and regional geology were the main influencing factors for water quality in most rivers [34]. Diffuse pollution has also been reported to deteriorate water quality in water bodies [35–36]. Therefore, the study conducted a water quality assessment using GIS to be able to assess the spatial distribution of pollution problems. The analysis results identified 10 water quality parameters with the most frequent occurred to be exceeded the permitted levels in the study area (Figure 7). Additionally, PCA analysis indicated that these 10 parameters also play a pivotal role in the water quality variation by 4 main pollution sources and some secondary pollution sources (SM 3). By PCA analysis, four main water polluting sources explaining 87.3% variation of water quality were identified using eigenvalue of greater than 1.

The concentration of TSS were the lowest at the locations M5, M6, M12, M14 – M16 (42–52 mg L^{-1}) (Figure 7a) and these places were not mainly affected by urban activities. The highest TSS was found at the monitoring positions M6 – M8, M10 and M19 (100–252 mg L^{-1}) because these places were affected by the daily activities of the urban area, small river basins, poor water circulation. As can be seen that TSS concentration at the sampling locations depended on the characteristics/sources of wastes of each location, and less susceptible to diffusion of pollution from other locations.

The concentration of DO varied from 4–6 mg L^{-1} which was considered optimal for the growth of aquatic organisms [37–38]. The average DO concentration over the sampling period was relatively low, ranging from 2.5–4.3 mg L^{-1} (Figure 7b). The spatial distribution of DO showed that the water quality was divided into two areas, the first area was included the sites M4, M6, M9, M10, and M14 and the second area were the remaining locations where the DO could harm to aquatic life (2.5–3.1 mg L^{-1}) [39]. Besides that, BOD, COD, and TOC parameters are indicators of organic pollution in the water environment, when the concentration of these parameters tended to increase, the level of organic pollution increases [40]. BOD, COD and TOC concentrations ranged from 3.5–9.6 mg L^{-1}, 14–42 mg L^{-1} and 3.4–12.5 mg L^{-1}, respectively; these parameters at all locations exceeded the limits of QCVN 08-MT:2015/BTNMT (Figure 7c, 7d, 7e). This underlines the presence of organic pollution sources at the monitoring locations. The distribution of pollution levels of BOD, COD, and TOC at the monitoring locations was almost similar. Specifically, the two locations M4 and M14 have the lowest pollution level (BOD = 3.6–4 mg L^{-1}, COD = 14–20 mg L^{-1} and TOC = 3.38–5 mg L^{-1}); the locations of high pollutant concentrations including M1, M2, M3 and M7 (BOD = 6–9.6 mg L^{-1}, COD = 20–42 mg L^{-1} and TOC = 10–12.5 mg L^{-1}). Furthermore, the problem of TOC pollution was also recorded at M11 and M12 sites, which were the largest shrimp farming area in the province [41]. According to research by Van et al. (2018) [42], the concentration of TOC that shrimp accumulated from feed was only about 18.0–18.8%, the remaining TOC discharged into the pond and outside environment (81.8–82%). Consequently, excess feed and chemicals for pond treatment may have contributed to TOC contamination in the water at M11 and M12 locations.

The concentration of ammonium ranged from 0.09–3 mg L^{-1}, in which the locations in the central area of the Soc Trang Province (M1 – M3 and M17) had the highest pollution level (Figure 7f). In addition, M7 location was also recorded with high ammonium concentration. The ammonium source could be related to the use of fertilizers and pesticides in agriculture since M7 is the major agricultural cultivation area of the province (shrimp farming, crop and rice farming) [43]. In addition, because the DO concentration was low, NH_4^+-N cannot be converted to NO_3^--N, so NH_4^+-N was high in the water environment and NO_3^--N was not the main pollution problem in the study area. However, the nutrient concentration has the ability to stimulate eutrophication to occur, depleting the dissolved oxygen source in the water [44]. The map also presented that NO_2^--N has a high level of pollution in the central area of the province. NO_2^--N is an intermediate oxidation product of NH_4^+-N but it was usually more harmful to animals and humans than NO_3^--N [45]. Toxicity of NO_2^--N depended on the concentration of Cl^- (saltwater), NO_2^--N in freshwater conditions was much more toxic than salt or brackish water [46]. Therefore, this has limited the water use of people in areas with high pollution level of NO_2^--N.

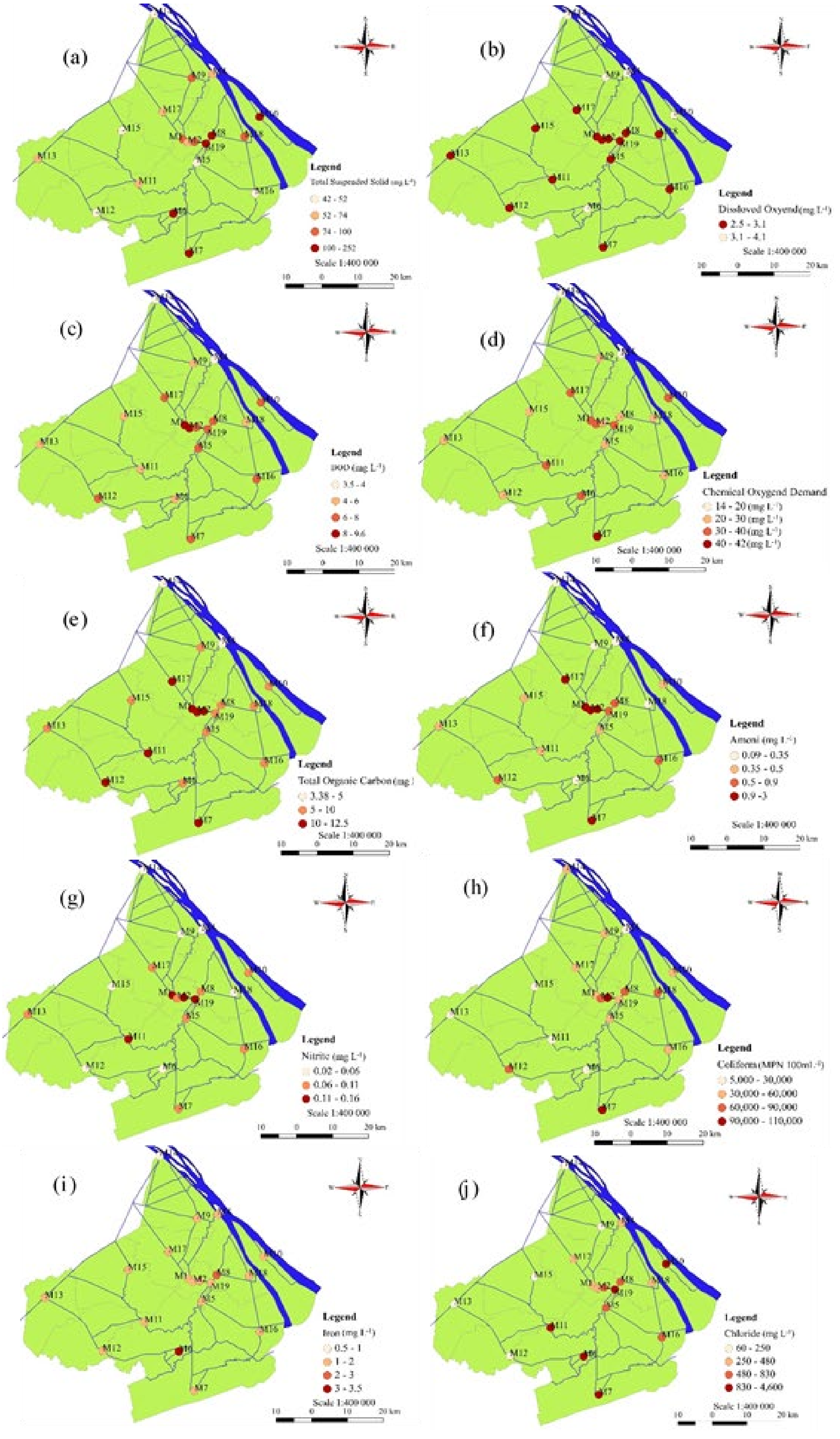

Figure 8 Spatial distribution of water quality pollution parameters in Soc Trang Province.

The coliform density was relatively high at all monitoring locations (5,000–110,000 MPN 100 mL^{-1}). Among the monitoring sites, the locations in the central area of the province/ district (M2, M3, M8, M18, M12) and the agricultural area (M7) had the highest coliform density (> 60,000 MPN 100 mL^{-1}) (Figure 7h). The presence of coliform in the water environment illustrated that the water environment polluted feces from human and warm-blooded animals [47]. On the other hand, the density of coliform was also affected by diffuse sources (leaching of livestock land) and some other environmental factors (pH, turbidity, salinity, and nutrient concentration) [48].

Figure 7i showed the distribution of total Fe in the study area with concentrations ranging from 0.5–3.5 mg L^{-1}. Fe concentration was in the range 1–2 mg L^{-1} at most of the research sites. The highest concentrations were found at site M6 and the lowest at site M14. The distribution of Fe concentration in the water is often related to the distribution of soil types [49], typically the M14 is characterized by alluvial soil while M6 site is salty and alkaline soil [50–51]. In addition, the presence of Fe in the water can be attributed to the washout of roads, buildings, and domestic wastewater. Chloride concentration at 19 monitoring locations varied from 60 – 4,600 mg L^{-1} and only 5 locations (less affected by seawater) were within the limits of QCVN 08-MT: 2015/BTNMT (250 mg L^{-1}) (Figure 7j). Previous research by Tuan et al. (2019) [26] also reported that the water quality from the Hau River and its tributaries in Ke Sach District (M4 and M14) had the lowest risk of saline effect. Meanwhile, the locations M6, M7, and M10 (near the sea), M11 and M19 (agricultural and urban areas) have the highest concentration of chloride compared to the other locations. The chloride concentration tended to gradually increase towards the sea contiguous areas (in the Southeast). The distribution of chloride polluted locations was similar to the saline intrusion trend along the canals to Soc Trang City [26]. This can be explained by salinity washing in the soil, the effects of seawater and/or human activities [52].

In general, the spatial distribution of pollution parameters indicated that the central pollution area of Soc Trang Province was M1, M2, M3 and M7 with pollution problems mainly organic matter (COD and TOC), nutrients (NH_4^+-N, NO_2^--N) and coliform. In addition, the distribution map of the water pollutants showed that the areas located in the interior fields and near the sea had lower water quality compared to the area adjacent to the Hau River; this may be because of the negative influence of human activities as indicated by Lien (2016) [31] and Rotirotu et al., 2019) [53].

Conclusion

The results indicated that water quality in Soc Trang was contaminated with TSS, organic matters, nutrients, microorganisms, Fe, and saline intrusion in the dry season. At locations M4, M9 and M14, the occurrence of water polluting parameters was lower than that at the other locations. Pollution frequency of the monitoring months tended to increase during the survey period, in which the frequency of pollution indicators in the dry season was lower than that of the rainy season. In addition, the water quality at the monitoring sites was classified from heavy to poor level and unsuitable for domestic, irrigation and other similar purposes based on WQI index (except M6 site). CA analysis has classified 19 sampling locations into 7 clusters and 19 monitoring months into 3 periods implying that the sampling locations could be significantly reduced and the sampling frequency could be performed three time per year (rainy season, dry season and end of the dry season - onset of the rainy season), saving approximate 75% of the monitoring costs during the year. The mapping of water polluting parameters using GIS indicated that the major water pollution sources were from urban and residential discharges, agricultural cultivation, and aquaculture and seawater impacts.

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