Surface Water Quality in Urban Areas in Southern Most Province of Vietnam

Tran Thi Kim Hong, Le Thi Diem Mi, and Nguyen Thanh Giao*

***Abstract*—This study aims to assess the influence of socioeconomic activities on surface water quality in the Ca Mau province. Water quality data were collected at 14 locations in 2021. Water quality index (VN_WQI), hierarchical cluster analysis (HCA), Pearson correlation and principal component analysis (PCA) were applied in the study. The results showed that the surface water quality was contaminated organic matters (TSS, BOD, COD) and coliform. Water quality was assessed from poor to medium levels by VN_WQI and the water quality is unsuitable for direct irrigation purposes. The results also showed that water quality at Ganh Hao river fork (S2) was the most polluted. HCA classified water quality into three groups based on the similarity of water quality parameters. Pearson correlation results indicated organic pollution, nutrients and microorganisms were mutually related. PCA explained 83.60% of the total variance with three PCs. Ten parameters were identified as the key water parameters influencing surface water quality and these parameters should be continuously monitored. The water pollution sources were possibly urban and market activities, production facilities discharge and salinity intrusion.**

***Index Terms*—Ca Mau province, hierarchical cluster analysis, surface water quality, nutrients, microorganisms**

I. Introduction

Water pollution happens when some unwanted constituents enter into the water bodies and change the water quality [1]. Surface water pollution has been one of the most concerning environmental issues in recent decades and it continues to pose a global threat to humans, biodiversity and aquatic organisms [2, 3]. Some negative for human health effects such as gastrointestinal diseases, damage to organs (heart and kidney) have been reported to be related to water quality [4, 5]. Besides, water pollution caused by toxic substances such as pesticides, heavy metals has been shown to cause acute and chronic effects, suppressing immune response, reducing metabolism, damaging the gills and epithelium in fish species [6]. At the same time, eutrophication due to an increase in nutrients in water bodies, leading to algal blooms in the water, depleting oxygen in the water, also negatively affects fish and other aquatic animal populations [5]. In addition, irrigation with poor quality water will reduce crop yield and soil quality [7]. According to [3] natural and anthropogenic activities are important factors in the accumulation and increase of concentrations of pollutants in the environment. In addition human activities, agriculture and industry considered are the three main pollution sources leading to increasingly serious deterioration of surface water quality [5, 8]. Over the last few decades, useful tools for supporting water quality management have steadily increased, in which multivariate statistical analysis technique is considered as one of the most effective tools, has been widely used to assess changes in surface water quality [3]. Multivariate statistical techniques have been applied such as principal component analysis (PCA), hierarchical cluster analysis (HCA), correlation analysis (Pearson) and discriminant analysis (DA), interpreting complex databases, evaluating temporal and spatial variations in surface water quality, and identifying the potential sources of water contamination [9–12].

Ca Mau province is located in the southernmost part of the Mekong Delta, is within the seawater intrusion zone with a total area of 5,221.2 km^2 and a population of 1.23 million people. Ca Mau is a flat and low-lying area that is regularly flooded because of its low elevation from −1 to 3 m above sea level and is strongly influenced by both East and West Sea tidal regimes with a network of rivers and canals interlaced, accounting for 3.02% of the natural area, in which there are many large rivers such as Cua Lon, Ganh Hao, Bay Hap, Song Doc, Dam Doi, Cai Tau [13]. According to [14], the main rivers in the Ca Mau province have been seriously polluted due to industrialization, urbanization and agriculture activities. The most obvious adverse effects are domestic and industrial wastewater discharged into the Ganh Hao River (Ca Mau City) causing the river water to emit an unpleasant odor. In addition, it was demonstrated that all rivers and canals in Ca Mau city were not able to receive any more COD and BOD_5 pollutant loads; and almost rivers and canals could not acquire any more pollutant load of NH_4^+-N and PO_4^{3-}-P, only Ca Mau River was able to receive wastewater with pollutant load of NH_4^+-N and PO_4^{3-}-P is 273.75 kg/day and 130.60 kg/day, respectively [13]. Besides, surface water in urban areas in the province is assessed as locally polluted, especially the section through Ca Mau city, where the population density is high but domestic wastewater has not been treated and discharged directly to rivers. However, these rivers are an important source of water for agriculture and aquaculture in Ca Mau Province. Therefore, it is necessary to monitor and evaluate the surface water quality in urban areas. The objective of this study was to assess surface water quality in urban areas in Ca Mau province and identity the pollution sources that contribute to changes in surface water quality as well as design a more suitable monitoring network in the future based on the water quality index and multivariate statistical analysis.

II. Materials and Methods

A. Study Site and Data

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Tran Thi Kim Hong, Le Thi Diem Mi, and Nguyen Thanh Giao are with College of Environment and Natural Resources, Can Tho University, Vietnam.

*Correspondence: ntgiao@ctu.edu.vn (N.T.G.)

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Surface water samples were collected on the main rivers and canals in the study area in 2021 (S1-S14), including S1 - Phung Hiep canal, S2 – the junction of the Ganh Hao river, S3 - Ca Mau canal, S4 - Trem river, S5 – the junction of the Bien Nhi canal, S6 - Ong Doc river, S7 – the junction of the Cai Nuoc river, S8 - Cai Doi river, S9 – the junction of the Tat Nam Can river, S10 - the Tan Tien commune junction, S11 - the junction of the Dam Doi river, S12 - ship parking area at Dat Mui restaurant, S13- Nha Phan market intersection and S14-Bay Hap river. At each sampling station, mixed water samples were collected in plastic bottles at a depth of 30–50 cm below the water surface. The location of the sampling points is shown in detail in Fig. 1.

Collected water samples, were analyzed for 10 parameters including salinity, pH, total suspended solids (TSS), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium (NH_4^+-N), nitrate (NO_3^--N), orthophosphate (PO_4^{3-}-P) and coliform. Analyzed according to standard methods prescribed by the Ministry of Natural Resources and Environment. Specifically, salinity was determined according to SMEWW 2520B:2017, pH was measured according to TCVN 6492:2011, DO was determined according to ASTM D 888-12, TSS was analyzed according to TCVN 6625:2000, BOD_5 was analyzed according to TCVN 6001-1:2008, COD analyzed according to SMEWW 5220C:2017, NH_4^+-N analyzed according to SMEWW 4500NH_3-B&F:2017, PO_4^{3-}-P analyzed according to SMEWW 4500-P-E:2017, NO_3^--N analyzed according to SMEWW 4500-NO_3-E-2017 and coliform were analyzed according to TCVN 6187-2:1996. Data on criteria for assessing surface water quality of Ca Mau province in 2021 is collected from the Department of Natural Resources and Environment of Ca Mau Province.

B. Data Processing

Surface water quality in urban areas in Ca Mau province were compared with QCVN 08-MT:2015/BTNMT Column B1-Quality of surface water for irrigation purposes or other uses with similar water quality requirements [15]. In addition, the water quality index (VN_WQI) is also applied in the study to show the status of water quality and the usability of that water source at each specific location. The water quality index is calculated according to Decision No 1460/QD-TCMT on technical guidelines for calculation and publication of water quality index of Vietnam (VN_WQI) [16]. In the study, 7 environmental parameters including pH, COD, BOD_5, NH_4^+- N, NO_3^--N, PO_4^{3-}-P and coliform were selected to calculate the water quality index, according to formula (1) and presented as a geographic map through the software QGIS version 3.16 (the Open Source Geospatial Foundation-OSGeo, Chicago, IL, USA).

$$WQI = \frac{WQI_I}{100} \times \left[\left(\frac{1}{k} \sum_{i=1}^{k} WQI_{IV} \right)^2 \times \frac{1}{l} \sum_{i=1}^{l} WQI_V \right]^{\frac{1}{3}} \quad (1)$$

where: WQI_I: Calculated WQI value for pH parameter; WQI_{IV}: Calculated WQI value for 5 parameters: COD, BOD_5, NH_4^+-N, NO_3^--N and PO_4^{3-}-P; WQI_V: Calculated WQI value for the coliform.

Multivariate statistical analyzes including Pearson correlation, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were performed in the study. First of all, Pearson correlation analysis was performed to find the relationship between water quality parameters [9, 17]. The closer the correlation coefficient (r) is to 1, the stronger the correlation between the environmental variables and the linear correlation [18]. The next, PCA analysis was performed to extract important environmental variables that contributed greatly to the change in surface water quality in the study area. The Varimax axis rotation method is defined by PCA. Eigenvalues of the principal components greater than 1 are considered significant and the first principal component will contribute the most to the change in water quality [19]. In addition, from the results of PCA analysis, it also helps to identify possible pollution sources in the study area [19, 20]. In this study, data of 10 surface water quality parameters at 14 monitoring sites were used for PCA analysis. In which, the Kaiser – Meyer - Olkin test (KMO) and the Bartlett Sphericity test were conducted to measure the suitability of the data for principal component analysis. In other words, it tests the adequacy of the sample size [21–23]. Finally, HCA analysis was used to classify monitoring sites based on physicochemical and biological characteristics of water quality [24, 25]. Correlation analysis and hierarchical cluster analysis were performed using SPSS software, version 20.0, and principal component analysis was performed using Primer software, version 5.2.

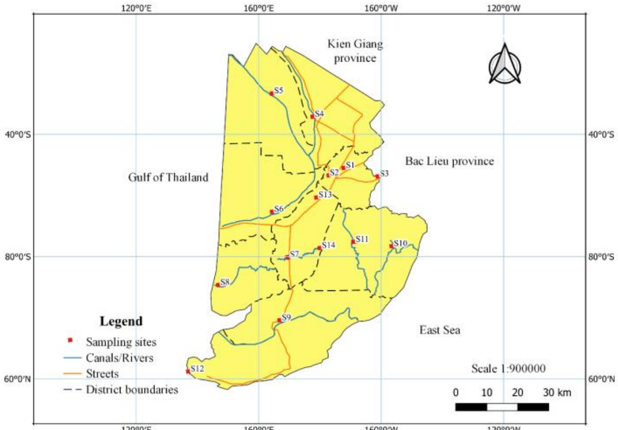

Fig. 1. Location of surface water monitoring stations in Ca Mau province.

III. Results and Discussion

A. Evaluation of Spatial Variation in Surface Water Quality in Ca Mau Province

- *pH and Salinity*

According to Chau *et al.* (2021), the pH value in surface water that is considered suitable for irrigation use ranges from 5.5–7.5, if the pH is higher than 7.5, crop yield will be affected [26]. The research results showed that the pH value relatively evenly according to the observation space, ranging from 6.97–7.79 and reached the average value of 7.43±0.24 (Fig. 2a). With this result, surface water quality in the study area is still within the allowable limit of QCVN 08-MT:2015/BTNMT column B1 (pH 5.5–9). At the same time, pH values were recorded similarly to the other water bodies of the Mekong Delta. In An Giang and Vinh Long provinces, the pH values fluctuated in the range of 7.15–7.22 and 7.08–7.94 respectively [12, 27]. In addition, compared with previous studies in the water bodies of Ca Mau province, the pH value did not fluctuate much, still within the allowable limit of the standard [13, 28].

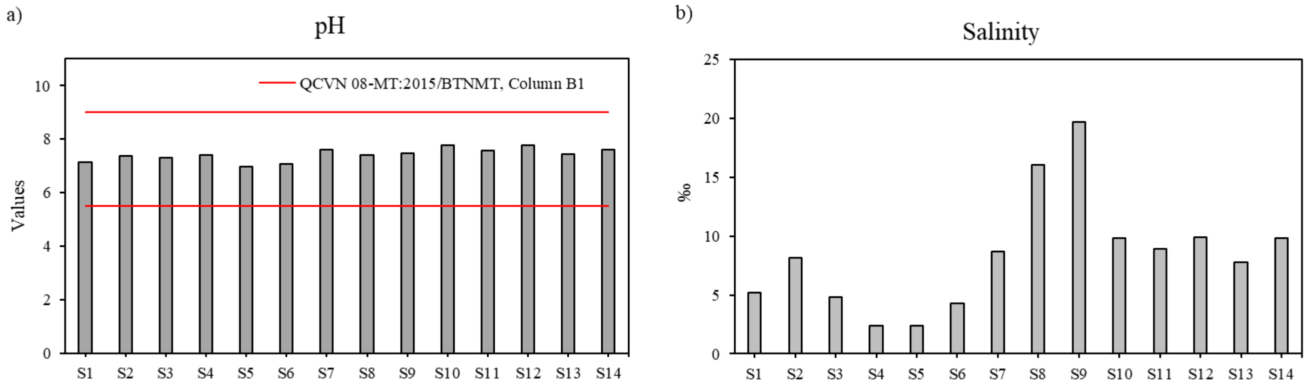

Fig. 2. pH and salinity in surface water in the study area.

According to Sommay (2017), fresh water has a salt value of from 0.02 to 0.5 ppt which suitable for the growing needs of crops [26]. Besides, white shrimp (*Litopenaeus vannamei*) can tolerate a large range of salinities (0.5–45 ppt) and grow appropriately where the salinity is about 10–15 ppt [26]. The research results showed that the salinity in water at 14 monitoring locations in Ca Mau province fluctuated relatively large from 2.38–19.66‰. The lowest and the highest value are recorded at S4-Trem river and S9-the junction of the Tat Nam Can River, respectively (Fig. 2b) with an average value of 8.42±4.84‰. It can be seen that the salinity value in surface water in the study area is relatively high, which can affect the growth and development of many crops when using this irrigation water source [29]. These locations are at estuaries bordering the sea and saline intrusion from the sea into the river is quite common, especially in the dry season and the salinity will decrease when moving deeper into the field [30]. At all monitoring locations, the presence of salinity was recorded in the water, which shows that the saltwater intrusion process has moved into the water bodies of Ca Mau Province and tends to go deeper into the inland areas, especially in the freshwater area north of Ca Mau [31]. The results of the present study tend to be lower than some monitoring locations adjacent to the East Sea and West Sea, the salinity fluctuated in the range of 23.5-28.8‰ [32]. However, this result compares well with the study in Ben Tre province, salinity ranged from 0.6–27.3‰ [33].

- *Suspended solids and oxygen demand*

Total suspended solids fluctuate from 58–322 mg/L with an average of 139.5±81.64 mg/L. The lowest value is recorded at S1 - Phung Hiep canal and the highest are recorded at S9-the junction of the Tat Nam Can River, respectively (Fig. 3a). Research results have shown that all monitoring positions in the study area exceed the allowable limit of QCVN 08-MT:2015/BTNMT column B1 (TSS 50 mg/L) from 1.16-6.44 times. Besides, when compared with a previous study, TSS content in water affected by urban activities tends to increase [13]. Specifically, in the period 2017-2018, TSS concentrations were only recorded in the range of 50-221 mg/L. In addition, high TSS concentrations in the surface waters and exceeding the allowable limit of the standard were also recorded in many water bodies in the Mekong Delta such as Soc Trang, An Giang and Hau Giang Provinces with values of 95.79±8.45 mg/L, 53.33±3.59–59.59±8.82 mg/L and 53.6–73.6 mg/L, respectively [12, 19, 34] and TSS contamination of surface water is one of the main concerns of the region. TSS can clog fish gills, either killing them or reducing their growth rate [35]. This leads to a decrease in photosynthesis and oxygen production by algae, the resultant decrease in primary production reduces food availability for aquatic organisms higher up the food chain. When suspended solids settle out to the bottom, they may bottom-dwelling plants and animals. In addition, high suspended solids in water also cause difficulties for drinking water treatment and increase the cost of water treatment [36].

Dissolved oxygen is an important parameter in water quality assessment because it is essential for all aquatic life, the chemical and biological processes taking place in water bodies are largely dependent on the presence of oxygen [36]. The research results showed that the DO concentration at 14 monitoring sites was relatively low, only fluctuating in the range of 1.92–5.74 mg/L with an average of 3.71±1.21 mg/L, corresponding to the lowest at the location S2 – the junction of the Ganh Hao river and the highest point at position S12-The tourist boat parking area at Dat Mui restaurant (Fig. 3b**)**. DO concentrations less than 5 mg/L may adversely affect functioning and survival of biological communities, and DO concentrations less than 2 mg/L may lead to death of most fish species [35]. From that, it can be seen that the DO content in surface water in the study area is no longer suitable for organisms to grow. Compared with the previous study [33], the DO concentration at monitoring points in Ben Tre Province is relatively higher, ranging from 5.33–6.97 mg/L. Similarly, in the water bodies observed in the study by [17], DO concentration ranged from 9.1–14.1 mg/L which is higher than the current study area. However, the results of the comparative study are good, with similarities with the report of [34], concentrations of DO in water bodies of Can Tho city, Hau Giang and Soc Trang Province ranged from 3.11±0.64 to 5.68±0.16 mg/L. The low DO value may indicate organic pollution in the water [35], originating from domestic and production wastewater arising from residential areas, urban areas, and market centers in the study area. In general, the DO concentration in surface water in the study area did not reach the threshold prescribed by QCVN 08-MT:2015/BTNMT (DO ≥ 4 mg/L), in particular at 6 locations (S4, S5, S6, S8, S10 and S12) have a DO content greater than 4 mg/L.

Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) are used test to establish concentration of the organic and inorganic pollution in water environment, respectively. As a result, the BOD_5 content fluctuates not much, ranging from 13 mg/L (S12 - the tourist boat landing area at Dat Mui restaurant) to 41 mg/L (S2 – the junction of the Ganh Hao river) with an average of 23±7.42 mg/L (Fig. 3c). From this result, it can be seen that most of the monitoring locations have BOD_5 content exceeding the allowable limit of QCVN 08-MT: 2015/BTNMT (BOD_5 15 mg/L) from 1.07 to 2.74 times. Only two locations of S12 (13 mg/L) and S14 (15 mg/L) is within the allowable limit, however, in the future receiving more wastewater that is not thoroughly treated, it will increase the organic pollution in water. Similarly, COD content fluctuated in the range of 14-67 mg/L with an average of 36.29±15.32 mg/L, also the highest concentration was at the S2 – the junction of the Ganh Hao river (Fig. 3d). In general, the average COD content in water bodies affected by urban activities in the Ca Mau province has exceeded the allowable limit of QCVN 08-MT: 2015/BTNMT (COD 30 mg/L) and has up to 9/14 monitoring positions exceed the standard from 1.03-2.23 times. Organic pollution in water bodies can come from a large amount of domestic and production wastewater in residential areas, urban areas, and markets in the area, which is untreated or only partially treated discharged directly into the receiving water, and when the amount of organic matter is high, it can reduce the amount of dissolved oxygen in surface water [37]. The location of Ganh Hao river, where the wastewater of production plant is received, has been seriously polluted by organic matter, similar to the present study results at site S2 with the highest BOD_5 and COD content, and the lowest DO among the 14 monitoring locations [13]. In addition, the BOD_5 and COD concentrations in surface water in the study area in 2021 tend to increase compared to the previous year (2020), recording only 16.5±5.3–16.9±7.1 mg/L and 29.2±9.2–29.9±11.5 mg/L, respectively [28]. The problem of organic pollution is also recorded in many water bodies. Surface water quality in Uong river was seriously polluted with high levels of BOD_5 and COD in 6 water samples, recorded from 18.2–48.2 mg/L and 32.3–124.9 mg/L, respectively [38]. Similar results were also found in the previous studies [39, 40].

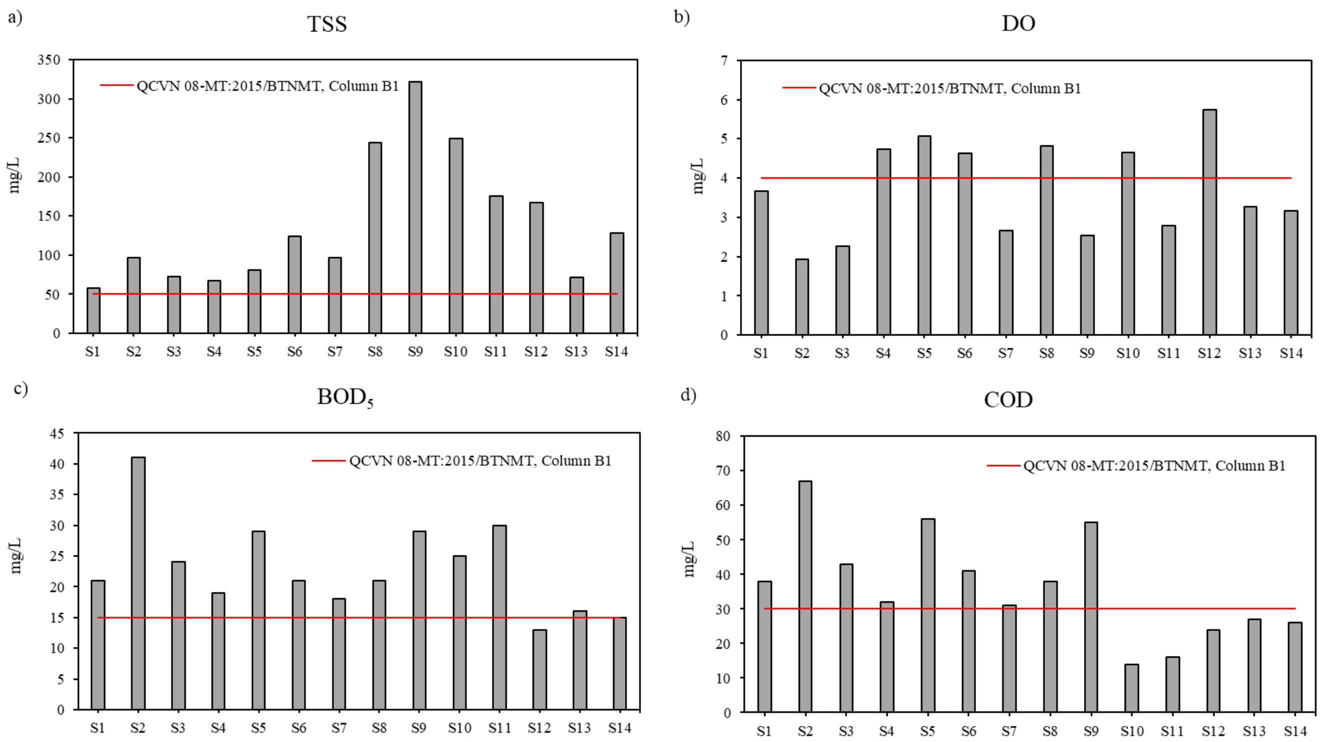

Fig. 3. TSS, DO, BOD_5 and COD concentrations in surface water in the study area.

- *Nutrients*

Nutrients are one of the important parameters for water quality management because an overabundance of nutrients can cause algal blooms, which depletes dissolved oxygen in the water and cause pollution the aquatic ecosystem [37]. In the study, three nutrient parameters including ammonium (NH_4^+-N), nitrate (NO_3^--N) and orthophosphate (PO_4^{3-}-P) were analyzed and detailed in Fig. 4.

The concentrations of NH_4^+-N, NO_3^--N and PO_4^{3-}-P in 14 water samples were observed to fluctuate in the range of 0.1–3.36 mg/L (an average of 0.695±0.93 mg/L), 0–1.12 mg/ L (an average of 0.45±0.40 mg/L) and 0–1.02 mg/L (an average of 0.296±0.28 mg/L), respectively, and nutrients tend to be highest at the junction of the Ganh Hao river (S2). The presence of nitrate indicates that aerobic decomposition has taken place and that the organic matter has had time to fully oxygenate [40]. However, the results have shown that the oxygen content in the surface water is very low, so aerobic decomposition will hardly take place, thereby making the concentration of NO_3^--N very low in the study area. In addition, sources of nitrate contamination can come from livestock facilities, municipal wastewater and septic systems

[40, 41]. Detergents are the major source of phosphorus pollution in urban surface waters [42]. From that, it can be seen that the activities that can generate waste and wastewater in the study area have not significantly affected the nutrient content present in the water and changed the water quality. Compared with the study conducted in the Saigon River, the concentration of nutrients here tends to be higher, the PO_4^{3-}-P, NH_4^+-N and NO_3^--N concentrations were recorded from 0–1.168 mg/L, 0–13.92 mg/L and 0–54,545 mg/L, respectively [37]. In addition, all water samples observed in Uong river have very high concentrations of PO_4^{3-}-P and NO_3^--N, ranging from 0.28–0.64 mg/L and 11.24–17.92 mg/L, respectively, which is strongly influenced by discharge activities from production facilities as well as domestic wastewater from surrounding residential areas [38]. However, the present study results are similar to those reported in the previous study [27] that in the water bodies observed in Vinh Long Province, the concentrations of NH_4^+-N, NO_3^--N and PO_4^{3-}-P were 0.18–0.58 mg/L, 0.14–0.71 mg/L and 0.16–0.89 mg/L, respectively. In general, surface water quality in the study area is not contaminated with nutrients, with most monitoring locations still within the allowable limits of QCVN 08-MT:2015/BTNMT column B1. However, at positions such as S1, S2, and S5, the NH_4^+-N concentration was 1.29–3.73 times higher than the standard and at two positions (S1 and S2), the PO_4^{3-}-P content was 1.2-3.4 times higher than the standard.

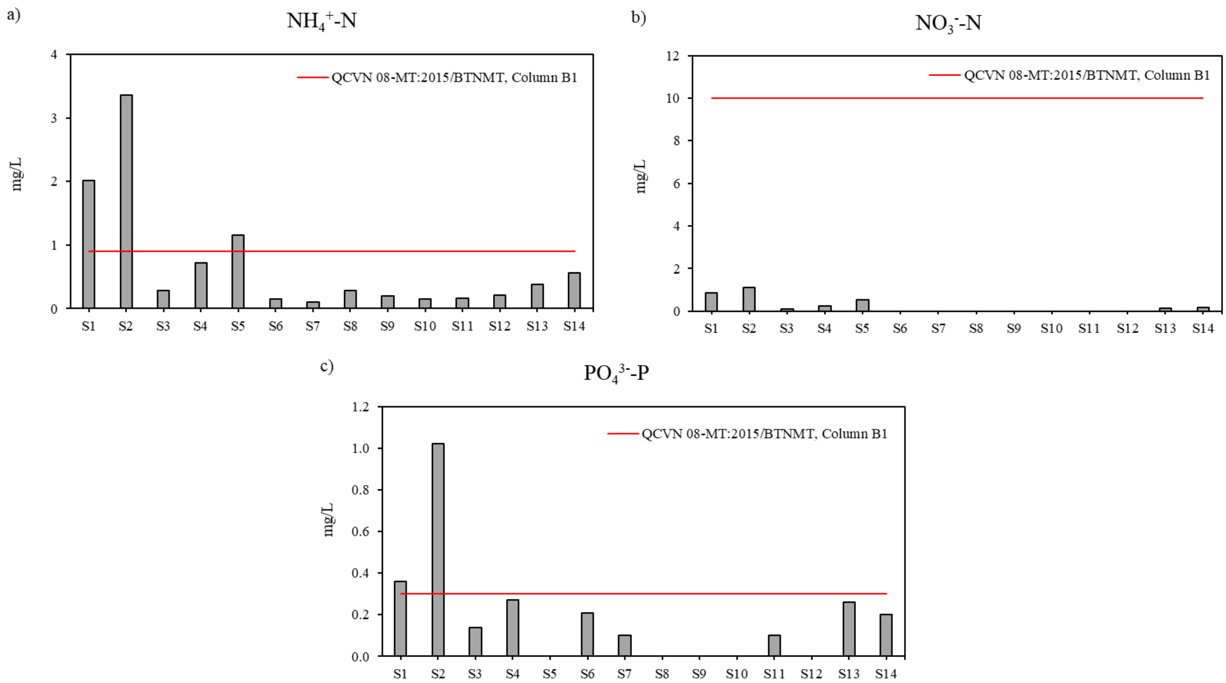

Fig. 4. Nutrient contents in surface water of the study area.

- *Coliform*

The use of untreated wastewater containing large amounts of microorganisms for irrigation can negatively impact human health as well as the quality of the environment including soil and crops [43]. In the study, the concentration of coliform detected in the water samples was very high, ranging from 3,900–150,000 MPN/100 mL with an average of 30,964.29–38,578.94 MPN/100 mL (Fig. 5). The concentration of coliform continued to be high in water samples belonging to the junction of the Ganh Hao river (S2) and the lowest in water samples at the junction of the Tat Nam Can River (S9). With this result, the concentration of coliform in surface water in the study area exceeded the allowable limit of QCVN 08-MT:2015/BTNMT column B1 (7,500 MPN/100 mL) and exceeded 1.6–20 times. Particularly at two locations (S8 and S9), the recorded coliform content was still within the allowable limit of the regulation. Human and animal feces are a serious source of microbial contamination in water [44]. In addition, this result shows that surface water in the study area is currently receiving a large amount of waste from livestock and domestic activities, especially excretory waste [45] and affect human health such as gastrointestinal diseases if using this polluted water source [46]. High levels of coliform and exceeding the allowable limit of QCVN 08-MT: 2015/BNTMT were recorded in many water areas in Vietnam such as the Uong river (10,810-16,800 MPN/100 mL) [38], Can Tho River in the period 2010-2011 (10,547-27,327 MPN/100 mL [47], the flowing Hau River through An Giang-Can Tho (14,200-31,500 MPN/100 mL) [45], water bodies in An Giang Province (11,067±2,168–31,363±11,476 MPN/100 mL) [12].

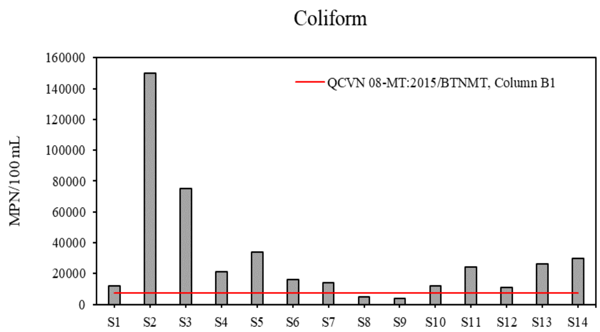

Fig. 5. Coliform content in surface water of the study area.

In general, surface water quality in the study area is affected by the activities of urban areas, residential areas, and market centers which have been polluted by organic and microorganisms with BOD_5, COD and coliform is high in water. In which, the location of the junction of the Ganh Hao river is assessed to have the highest level of organic and microbial pollution.

B. Water Quality Index (VN_WQI) and Grouping of Monitoring Locations

The water quality index is a composite index that is calculated from water quality parameters through a mathematical formula. VN_WQI is used for quantitative description of water quality and is expressed through a specified scale with different divisions of surface water quality. According to [16], the water quality index is divided into 6 levels with the following ranges of values (1) WQI < 10 indicates highly polluted, requiring remedial and treatment measures; (2) WQI from 10–25 indicates poor water quality that requires future remedial measures; (3) WQI from 26–50 indicates bad water quality, used only for transportation and other equivalent purposes; (4) WQI from 51–75 represents medium water quality, used for irrigation and other equivalent purposes, (5) WQI from 76–90 indicates good water quality, used for domestic water supply purposes but need appropriate treatment measures and (6) WQI from 90-100 shows excellent water quality, good for domestic water supply purposes. In the study, VN_ WQI index was calculated from data of 7 parameters including pH, BOD_5, COD, NH_4^+-N, NO_3^--N, PO_4^{3-}-P and coliform at 14 monitoring locations and the spatial distribution of VN_ WQI index in the study area is detailed in Fig. 6. The results showed that the VN_WQI values at these monitoring sites are from poor to medium (from 22.95 to 65.52). The quality of surface water that can be used for irrigation and other equivalent purposes only appears at S8 and S9 (WQI 51–75), accounting for 14.29% of the total. There are 11 locations (accounting for 78.57%) with surface water quality used only for transportation and other equivalent purposes (WQI 26–50). Especially, at the junction of the Ganh Hao river (S2), surface water quality is highly polluted. Therefore, it can be seen that surface water in the study area is unsuitable for irrigation purposes. The water quality index has the advantage of showing the status of water quality, thereby making choices for effective use and management of water resources [47–51].

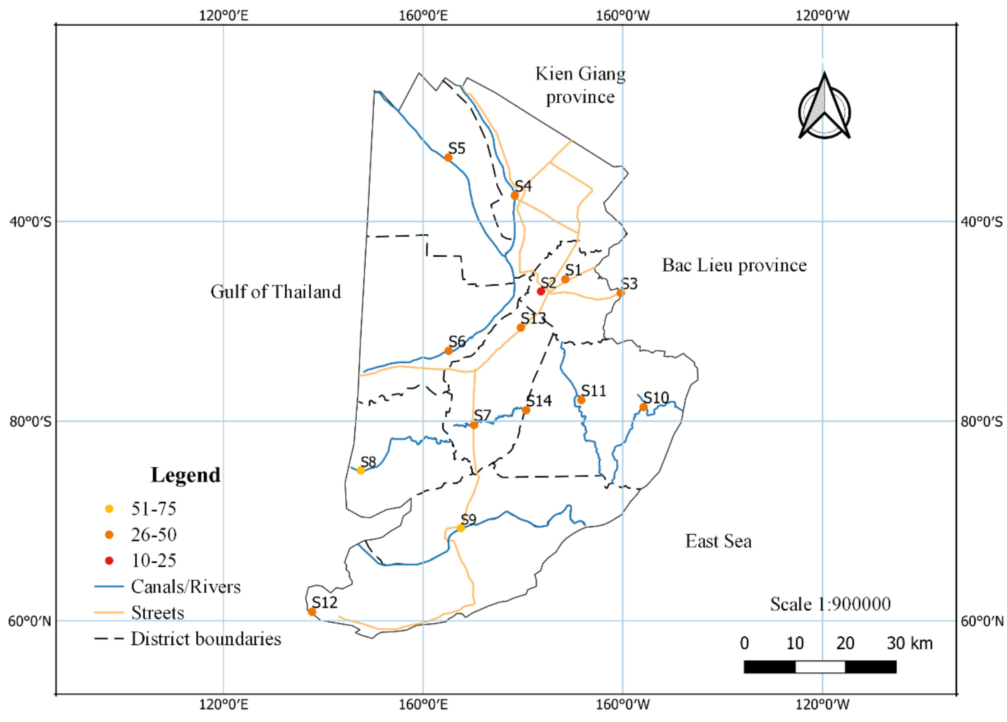

Fig. 6. Spatial distribution of WQI in water bodies in the study area.

Hierarchical cluster analysis (HCA) is performed from the data of 10 surface water quality parameters that vary by space and the results of HCA analysis are shown in Fig. 7. With 3 groups of surface water quality was formed from the process of analyzing the similarity of physio-chemical and microbial characteristics in 14 water samples, with increasing pollution levels. Group I gathered the most sites with eight sites with similar surface water quality (S7, S8, S9, S10, S11, S12, S13, S14), group II gathered five sites (S1, S3, S4, S5, S6) and group III represent a separate position, S2. According to this classification order, group I represents the locations with the least polluted surface water quality, similar to the analysis results of the VN_WQI index at these sampling points higher than the remaining monitoring locations. The next, group II has more polluted surface water quality, these locations were identified with low VN_WQI in the previous analysis. Finally, group III with a separate location – the junction of the Ganh Hao river has highly pollution, similar to the results of the VN_WQI index. In addition, the analysis results also show that the water quality groups not only have a large difference in the concentration of pollutants but also the salinity in the water (Table I). Specifically, group I, the collection of sampling points bordering the sea, is influenced by seawater intrusion, leading to higher salinity in the water than the other groups and the lowest concentration of pollutants in this group. Since water samples were collected in different rivers in the study area, the HCA analysis only shows the similarity between the monitoring locations as well as the water pollution status and need to continue to monitor and evaluate in the future. In order to find the similarity in water characteristics between the observed locations, HCA analysis has been applied in many studies [22, 52, 53]. However, in the monitoring network, if the monitored locations have similar water quality, are influenced by the same impact sources, and are located on the same water area, hierarchical cluster analysis could help narrow the scope of observation [54, 55]. As a result, the hierarchical CA technique is very useful in water quality classification and the number of sampling sites and associated monitoring costs can be reduce without much missing information.

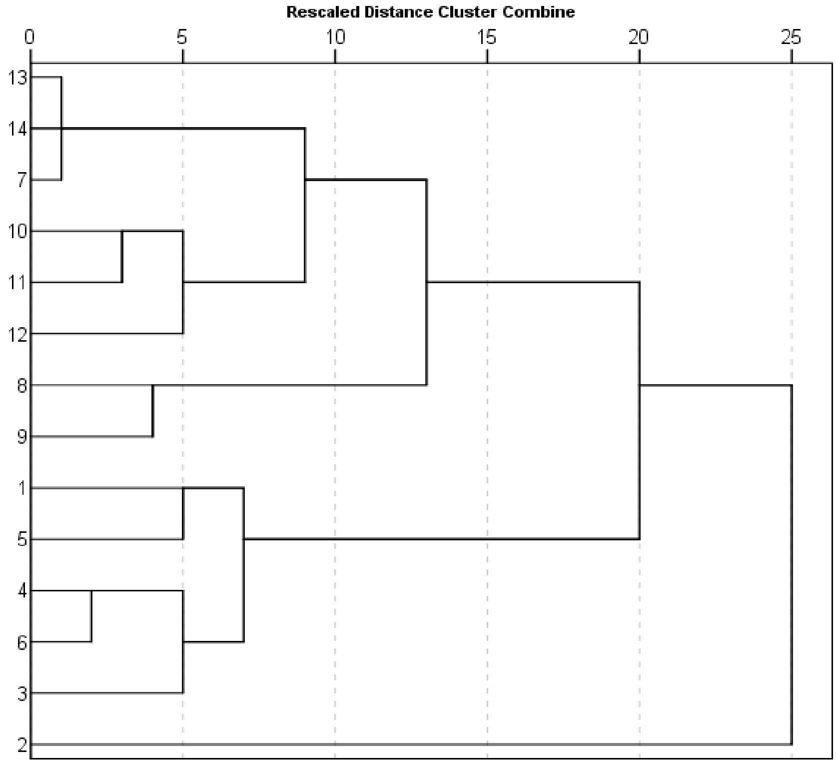

Fig. 7. HCA analysis results.

TABLE I: AVERAGE VALUES OF SURFACE WATER ENVIRONMENTAL INDICATORS IN EACH GROUP

Parameters	Unit	Group I	Group II	Group III
Salinity	‰	11.33	3.82	8.12
pH	-	7.59	7.19	7.36
TSS	mg/L	181.63	80.60	97
DO	mg/L	3.70	4.08	1.92
BOD_5	mg/L	20.88	22.80	41
COD	mg/L	28.88	42.00	67
NH_4^+-N	mg/L	0.26	0.87	3.36
NO_3^--N	mg/L	0.04	0.35	1.12
PO_4^{3-}-P	mg/L	0.08	0.20	1.02
Coliform	MPN/100 mL	15,687.50	31,600	150,000

C. The Relationship and Origin of Pollution Sources in the Study Area

The Pearson correlation coefficient matrix for water bodies in the Ca Mau province affected by urban activities is presented in Table II. The results show that the parameters in the water samples are correlated at $p < 0.01$ and $p < 0.05$ level. Parameters characteristic for organic and nutrient pollution in water including BOD_5, COD, NH_4^+-N, NO_3^--N and PO_4^{3-}-P have strong positive correlation with correlation coefficient (r) ranges from 0.506–0.983, and these water quality indicators are essentially indicators of oxygen consumption in water [20]. Besides, a positive correlation was found between BOD_5 and COD with correlation coefficient r reached 0.609. At the same time, the BOD/COD ratio is greater than 0.5, indicating that the surface water is organically polluted and biodegradable [55]. In addition, the results also show that most of the environmental indicators have a positive correlation with coliform. Specifically, BOD_5, COD, NH_4^+-N, NO_3^--N and PO_4^{3-}-P had a correlation coefficient with coliform of 0.656, 0.567, 0.735, 0.666 and 0.828 respectively, while DO had a negative correlation with coliform (r = -0.534). Linear correlations between organic pollutants and nutrients were also found in several studies [20, 56, 57]. According to [58], the water environment indicators appear to be linearly correlated with each other, indicating that they have the same origin. Organic, nutritional and microbial pollutants can come from domestic wastewater in residential areas, urban areas and markets as well as wastewater from production facilities in the study area. The study results also found a positive correlation between salinity and TSS, which is similar to the results of previous studies [59, 60]. The reason is that more dissolved salts can lead to higher liquid densities and lower settling rates of particles of the same size, so TSS tends to increase with salinity [59].

TABLE II: CORRELATION COEFFICIENT MATRIX

Parameters	Salinity	pH	TSS	DO	BOD_5	COD	NH_4^+-N	NO_3^--N	PO_4^{3-}-P	Coliform
Salinity	1									
pH	0.475	1								
TSS	**0.865****	0.433	1							
DO	-0.183	-0.035	0.089	1						
BOD_5	0.062	-0.304	0.148	-0.452	1					
COD	0.004	**-0.646***	-0.106	-0.289	**0.609***	1				
NH_4^+-N	-0.254	-0.383	-0.397	-0.280	**0.588***	**0.617***	1			
NO_3^--N	-0.356	-0.477	-0.481	-0.234	**0.539***	**0.606***	**0.983****	1		
PO_4^{3-}-P	-0.254	-0.215	-0.443	-0.471	**0.506***	0.482	**0.869****	**0.799****	1	
Coliform	-0.247	-0.187	-0.370	**-0.534***	**0.656***	**0.567***	**0.735****	**0.666****	**0.828****	1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

The result of the KMO and the Bartlett's Sphericity Test showed that the data were adequate for principal component analysis [21–23], which has a value of about 0.55 and $p < 0.05$, respectively. In PCA analysis, eigenvalues are often used to identify principal components (PCs) [61]. Principal components with eigenvalues greater than 1 should be retained, to explain the variability of information contained in the original data [19, 51]. The scree plot (Fig. 8) shows that there are three important components contributing to the explanation of surface water quality fluctuations in the study area. PC1, PC2 and PC3 explain up to 83.60% of the total variance of the information contained in the original data. According to [45], the absolute values of the loading factors differ in significance with strong correlation (>0.75) moderate correlation (from 0.75 to 0.5) and weak correlation (from 0.5 to 0.3) between the water quality parameters and the principal component [45]. Table III shows the results of PCA analysis. At the first principal component (PC1), which explains 50.80% of the total variance, has a weak correlation with most organic, nutritional and coliform pollutants. Specifically, COD, NH_4^+-N, NO_3^--N, PO_4^{3-}-P and coliform have loading factors of (−0.323), (−0.410), (−0.405), (−0.390) and (−0.380), respectively. Pollution sources can possibly domestic wastewater from urban and market areas, and production discharge in the study area. The sources of these pollutants have also been reported in the former studies [19, 20, 37]. In addition, in agricultural areas, the presence of PO_4^{3-}-P and NO_3^--N originates from the application of nitrogen and phosphate fertilizers to crops [9]. The second principal component (PC2) explains 20.80% of the total variance, has a moderate positive correlation with salinity (0.591) and a weak positive correlation with TSS (0.532) and BOD_5 (0.357), meanwhile, PC2 is negatively correlated with DO (−0.342) at a weak level. It can be seen that the oxygen content would decrease when the content of organic and TSS in the water increased. In addition, salinity intrusion was identified as one of the main sources of impact on the surface water quality in the Ca Mau province. At the third principal component (PC3), which explains 12% of the total variance, has a strong correlation with pH (0.602) in water, which is similar to the previous study [20]. From the analysis results, it is shown that all the monitoring parameters used in the study are suitable for assessing surface water quality in the study area. It can be implied that the water quality was influenced by several different sources such as domestic activities, urban areas, market areas, production facilities discharge and saline intrusion.

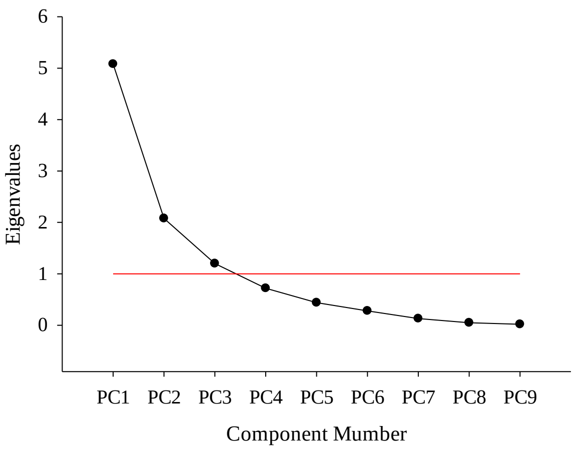

Fig. 8. Scree plot of eigenvalues.

TABLE III: PRINCIPAL COMPONENT ANALYSIS RESULTS

Variables	PC1	PC2	PC3
Salinity	0.170	**0.591**	-0.096
pH	0.240	0.269	**0.602**
TSS	0.228	**0.532**	-0.263
DO	0.197	**-0.342**	-0.373
BOD_5	-0.299	**0.357**	-0.197
COD	**-0.323**	0.160	-0.477
NH_4^+-N	**-0.410**	0.028	0.022
NO_3^--N	**-0.405**	-0.059	-0.034
PO_4^{3-}-P	**-0.390**	0.058	0.298
Coliform	**-0.380**	0.132	0.252
Eigenvalues	5.08	2.08	1.20
%Variation	50.80	20.80	12.00
Cum. %Variation	50.80	71.60	83.60

IV. CONCLUSIONS

Surface water quality in urban areas in Ca Mau province in 2021 has been polluted, as manifested by TSS, BOD_5, COD and coliform exceeding the allowable limit of QCVN 08-MT:2015/BTNMT column B1, while DO content is low, does not reach the limits. The VN_WQI index analysis results show that the surface water quality in the study area is poor to medium, is unsuitable for irrigation purposes. HCA analysis has classified 14 monitoring sites into three groups of surface water quality based on the similarity of physical, chemical and biological characteristics in the water. S2-the junction of the Ganh Hao river is assessed as having the highest pollution level. Pearson correlation analysis demonstrated that nutrients and microorganisms are closely correlated each other. Principal component analysis formed 3 PCs, explaining 50.80%, 20.80% and 12% of the total variance respectively, with all the parameters including salinity, pH, TSS, DO, BOD_5, COD, NH_4^+-N, NO_3^--N, PO_4^{3-}-P and coliform all contribute to the quality of surface water in the study area. The quality of surface water in Ca Mau province is influenced by many different sources such as urban and market activities, production facilities discharge and salinity intrusion. In this study only assessed the surface water quality affected by urban areas, therefore further research should comprehensively evaluate aspects that can affect water quality such as industry, agriculture, aquaculture in Ca Mau province.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

Tran Thi Kim Hong, Nguyen Thanh Giao and Le Thi Diem Mi designed the research and methodologies; Tran Thi Kim Hong and Le Thi Diem Mi conducted the research, analyzed the data and drafted the manuscript; Nguyen Thanh Giao revised and finalized the manuscript; all authors had approved the final version.

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