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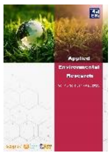

Research Article

Spatial and Temporal Trends in Surface Water Quality and Pollution Sources in Ben Tre, Vietnam: A Principal Component Analysis/ Factor Analysis-based Approach

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Abstract

Surface water quality is vital for maintaining ecological health and supporting sustainable development, particularly in the Mekong Delta, Vietnam, where water is heavily utilized. However, rapid urbanization and economic activities have led to water pollution. This study assessed the spatial and temporal variations in surface water quality in Ben Tre Province from January 2022 to December 2023 using 384 samples collected across dry and rainy seasons and two zones (headwater streams and cities). The water quality index (WQI) was calculated on the basis of 15 parameters, and principal component analysis/factor analysis was applied to identify pollution sources. Five key factors influencing water quality, explaining 66.95% of the total variance. These factors reflect the impacts of urbanization, agriculture, aquaculture, and natural conditions, with notable spatial differences in BOD_5, COD, nutrients, and suspended solids. Hierarchical agglomerative cluster analysis was applied to distinguish pollution vulnerability, In the dry season, two clusters emerged: headwater sites with good water quality and urban sites with elevated BOD_5, COD, nutrients, TSS, and coliforms. During the rainy season, three clusters were identified: a main group reflecting moderate runoff effects, a subset of sites with turbidity and nutrient spikes, and a single outlier (S35) with extreme iron and coliform levels under flood conditions. The WQI values revealed that water quality was better during the rainy season, with urban areas generally exhibiting higher WQIs than headwater streams. Correlation analysis highlighted the strong relationship between BOD_5 and COD (r = 0.99), while both were negatively correlated with WQI (r = -0.46 and r = -0.40, respectively). DO was positively correlated with WQI (r = 0.35) and inversely related to NH_4^+-N (r = -0.34). Fe was strongly positively correlated with WQI (r = 0.77). The organic and nutrient pollution exceeds regulatory limits in some areas, highlighting the need for improved wastewater management.

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Introduction

The surface water quality is under threat because of the increasing water demand and rising water scarcity [1]. Sustainable water resource management has become a critical concern in nations experiencing rapid economic growth and high population density [2]. The Vietnamese Mekong Delta, which accounts for approximately 21% of the national population and spans an area of 39,000 km², is one of the most densely populated regions in Vietnam [3]. The Vietnamese Mekong Delta is the primary rice-producing area, contributing nearly one-third of the country's economic output, primarily from agricultural activities [4]. The Mekong Delta also significantly supports national and export demands from aquaculture and agricultural production [5]. However, the intensification of aquaculture has led to the discharge of millions of cubic meters of wastewater annually, containing large quantities of biodegradable organic matter, nitrogen, phosphorus, pathogens, and sludge. Similarly, agricultural activities introduce substantial amounts of nitrogen, phosphorus, potassium, and pesticide residues, including insecticides, herbicides, fungicides, and other agrochemicals [6]. Urbanization and projected population growth further exacerbate the influx of contaminants into water bodies. Urban and rural communities contribute significant quantities of organic pollutants and pathogens through diffuse inputs, while point-source discharges from industries also play a substantial role [7]. In particular, food and seafood processing industries frequently release untreated effluents containing high levels of suspended particles, organic matter, nitrogen, phosphorus, and bacteria [8]. Many industrial parks and export processing zones in the region lack centralized wastewater treatment facilities [9–10], resulting in significant water quality degradation in areas of high population density and industrial activity [11].

In this context, evaluating surface water quality has become essential for nations worldwide. Climate change has compounded the water crisis, especially in coastal areas where freshwater resources are increasingly threatened by sea-level rise and human activities [12]. Although numerous studies have examined water quality in the Mekong Delta, most have focused on significant rivers or potential contamination sources [6, 13]. However, surface water quality in coastal areas has yet to be largely overlooked. In Vietnam, water quality monitoring is mandated under environmental protection legislation, with programs assessing physical, chemical, and biological parameters. These include temperature, pH, electrical conductivity (EC), total suspended solids (TSS), turbidity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), nutrients (e.g., NH_4^+ and PO_4^{3-}), heavy metals (e.g., Fe, Al, Mn, Cr, and Cd), pesticides, antibiotics, and biological indicators (e.g., Escherichia coli and coliform) [14]. Monitoring criteria and site selection were determined on the basis of budgetary constraints and pollution source characteristics according to national standards (QCVN 08-MT:2023/BTNMT) [15] and categorized via a water quality index (WQI) [16].

Multivariate statistical techniques, such as principal component analysis (PCA) and cluster analysis (CA), have recently gained prominence in water quality studies. These methods allow for the comprehensive incorporation of water quality data, identification of pollution sources and determination of critical water contamination parameters [17]. Given these theoretical foundations, monitoring water quality in regions affected by socio-economic development has become increasingly vital. Therefore, this study aimed to examine spatial and temporal variations in surface water quality in Ben Tre Province, Vietnam, by applying multivariate statistical techniques. The findings are expected to provide valuable insights for environmental management authorities, contributing to the assessment and improvement of surface water quality monitoring systems in the region.

Materials and methods

1) Study area

This study focuses on Ben Tre Province, which is located in the eastern coastal region of Vietnam's Mekong Delta [18]. The province is characterized by flat, low-lying terrain, with elevations typically ranging from 0.5 m to 1.5 m, covering approximately 70% of its natural area. A dense network of rivers traverses this region, bordering the East Sea to the east, featuring a 65 km-long shoreline. To the west and south, it is bounded by Vinh Long and Tra Vinh Provinces, which are separated by the Co Chien River, whereas the Tien River delineates its northern boundary with Tien Giang Province (Figure 1).

This study focused on the surface water system of Ben Tre Province, incorporating two research dimensions, spatial and temporal factors, across 32 sampling locations. The spatial dimension included two distinct partitions: headwaters (S1–S17) and cities (S18–S32), whereas the temporal dimension covered two seasons within a year—the dry season and the rainy season. Temporal variation was examined via surface water monitoring data collected over two years (2022–2023). The dry season was defined as occurring from May to November, whereas the rainy season spanned from December of the preceding year to April of the following year [19].

2) Water sampling and analysis

The surface water samples were monitored six times per year from 2022–2023, specifically in February, March, May, July, September, and November. During each sampling period, 32 surface water samples (S1–S32) were collected across two study areas (Figure 1), with 17 samples from the headwater-stream area and 15 from the urban area. The two-year study resulted in a total of 384 samples (32 samples × 6 periods × 2 years), ensuring a robust dataset for statistical analysis.

The sample collection process was carried out via a Van Dorn water sampler (3-1130-G42 Wild Supply Company, Wildco – US) [20]. Approximately 5 L surface water samples (0–50 cm) were collected via a Van Dorn water sampler. The samples were stored in acid-washed plastic bottles and kept in zipper plastic bags to prevent contamination. All the samples were transported in ice boxes with ice to the laboratory for further analysis. Water parameters such as pH (Thermo Scientific™ Orion™ 3-Star), temperature, and dissolved oxygen (DO) (Portable oximeter Oxi 3210) were measured in situ. Ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total iron (Fe), total suspended solids (TSS), phosphate (PO_4^{3-}), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total coliforms were analyzed in the laboratory on the basis of collected water samples according to the APHA method [21]. The concentrations of these parameters are expressed in mg L^{-1}, except for total coliforms, which were measured in MPN per 100 mL.

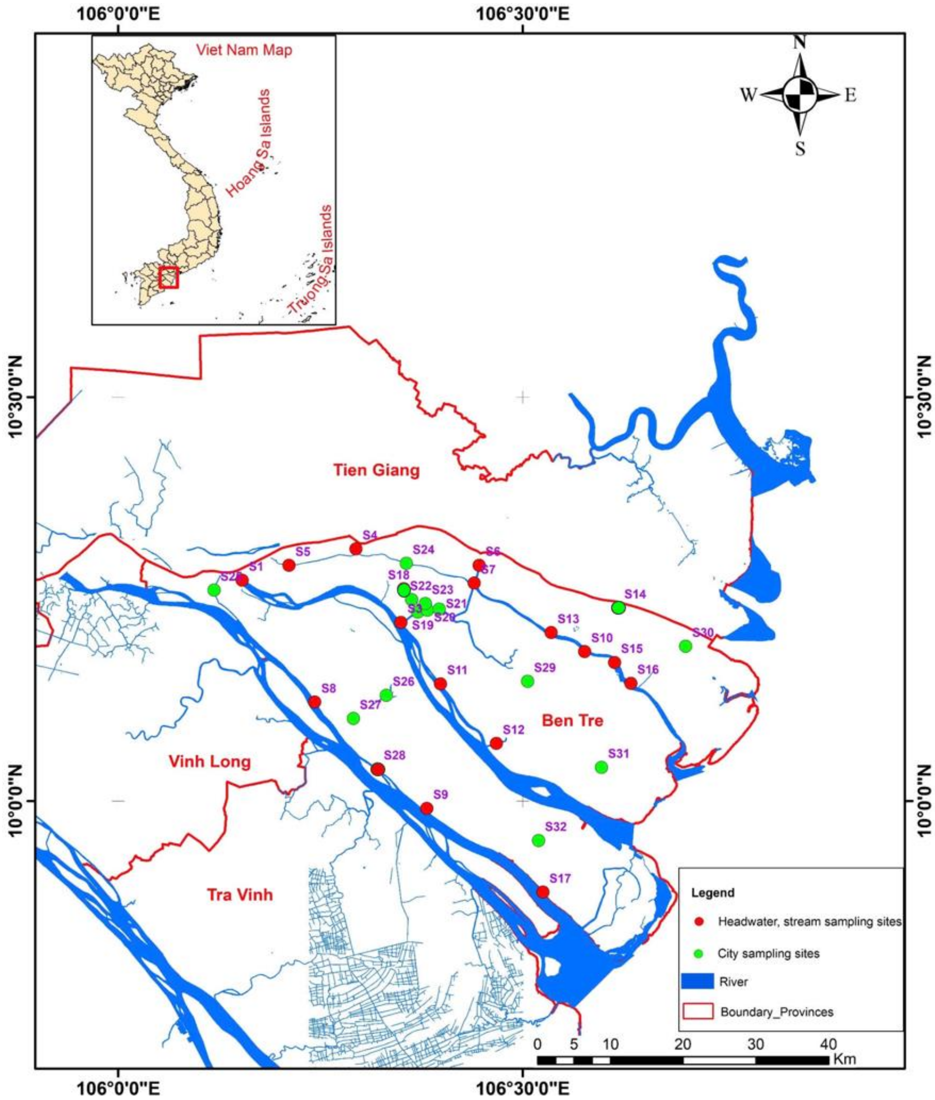

Figure 1 Map of the study area and sampling sites in Ben Tre Province, Vietnam

3) Statistical analysis of water parameters

3.1) Principal component analysis and factor analysis

Principal component analysis (PCA) and factor analysis (FA) were applied to the entire dataset to identify and separate pollution sources, following the procedures detailed in previous studies [22]. The WQI in this study was calculated via 15 water quality parameters on the basis of the results of PCA/FA, as described by Mukherjee and Lal [23]. The WQI was calculated via Eq. 1.

$$WQI = \sum_{i=1}^{n} w_i s_i \qquad \text{(Eq. 1)}$$

where n is the number of water quality parameters, wi is the weight of the i-th parameter, and si is the score of the i-th parameter. The weights (w^i) were determined from the PCA/FA results (Table 1), whereas the scores (s_i) were calculated via Eqs. 2 and 3. The WQI ranged from 0 (very bad quality) to 1 (very good quality) [24].

The 15 water quality parameters were classified into three groups: “the more, the better,” “the less, the better,” and “neutral.” The “the more, the better” group included only the DO parameter; the “neutral” group included pH, with values ranging from 5.5–9 [15]; and the “the less, the better” group included the 10 remaining parameters. For the “the more, the better” and “neutral” parameters, the value of s_i was calculated according to Eq. 2. The s_i values were calculated as follows:

For “the more, the better” and “neutral” parameters:

$$s_i = \frac{\chi_i - \chi_{min}}{\chi_{max} - \chi_{min}} \qquad \text{(Eq. 2)}$$

For “the less, the better” parameters:

$$s_i = \frac{\chi_{max} - \chi_i}{\chi_{max} - \chi_{min}} \qquad \text{(Eq. 3)}$$

where X_{max}, X_{min}, and X_i represent the analytical, minimum, and maximum values of parameter i, respectively.

The weights (w_i) for each parameter were derived from the PCA/FA results. Only factors with eigenvalues >1 were retained for further analysis, and the weights were calculated for parameters with high loading values (>0.5) for each retained factor rotation. The weights were determined via the following formula: e_i/sum (4), where e_i is the eigenvalue of factor i, and “sum” refers to the sum of the eigenvalues for all the retained factors after PCA/FA.

Table 1 The levels of the 12 water parameters in the two seasons considered in this study

Water parameters	Unit	Rainy season	Dry season	Total
Temperature	°C	29.19±0.71	29.17±0.87	29.18±0.79
pH	None	7.04±0.34	7.15±0.33	7.10±0.34
DO	mg L^{-1}	6.51±0.81	6.30±0.86	6.40±0.84
NH_4^+-N	mg L^{-1}	0.20±0.13	0.13±0.05	0.17±0.11
NO_3^--N	mg L^{-1}	0.46±0.37	0.34±0.18	0.40±0.29
PO_4^{3-}	mg L^{-1}	0.14±0.10	0.11±0.06	0.12±0.08
NO_2^-	mg L^{-1}	0.02±0.01	0.02±0.01	0.02±0.01
Fe	mg L^{-1}	0.73±0.27	1.03±0.58	0.88±0.47
BOD_5	mg L^{-1}	14.88±4.25	13.62±5.04	14.25±4.70
COD	mg L^{-1}	25.57±7.05	23.34±8.31	24.46±7.77
TSS	mg L^{-1}	55.14±41.24	60.21±34.78	57.68±38.14
Log(coliform)	**	3.22±0.28	3.23±0.29	3.22±0.29

Remark: The data are presented as the means ± standard deviations. ** is log (MPN per 100 mL).

3.2) Cluster analysis

In this study, CA was performed via Origin Pro software (Version 2021b, OriginLab Corporation, Northampton, MA, USA) to identify natural groupings among the monitoring sites on the basis of their environmental profiles. Clustering was performed on the basis of Euclidean distance, a widely used metric that quantifies the dissimilarity between observations by measuring the geometric distance between them in a multidimensional space [25, 26]. To ensure that variables with different scales did not disproportionately influence the clustering outcome, all variables were standardized via Z-scale transformation. This step effectively normalized the variance of each variable, mitigating the impact of scale differences on Euclidean distance computations [25–27]. Furthermore, the Ward method was selected as the clustering algorithm, as it is recognized for its robustness and efficiency in handling quantitative variables.

3.3) Two-way ANOVA

The validity and practicality of this method have been discussed in detail by Mukherjee and Lal [23]. Additionally, the WQI values were used in statistical analyses via two-way ANOVA via IBM SPSS Statistics (Version 29.0.2.0, IBM Corp., Armonk, NY, USA) to determine the contribution of potential pollution sources, as identified via PCA/FA, to the overall WQI [28]. Two-way analysis of variance was used to compare the differences in mean values between two independent categorical or ordinal variables and a continuous dependent variable. In this study, two-way ANOVA was used to determine the interactions between water quality parameters across seasons and study areas.

3.4) Pearson correlation analysis

In addition to spatial mapping, the correlation between water quality parameters and the water quality index was evaluated via Pearson correlation via JMP Pro software (Version 16, SAS Institute Inc., Cary, NC, USA). A statistical significance level of $p < 0.05$ was set.

Results

1) Principal component analysis/factor analysis

The PCA/FA analysis revealed that the Ben Tre Province surface water quality monitoring dataset was grouped into five factors with eigenvalues >1, collectively explaining 66.95% of the total variance (Table 2). Factor 1, the most significant, accounted for 25.84% of the total variance and presented high loadings for BOD_5 and COD. Factor 2 explained 12.98% of the variance and was strongly associated with NH_4^+-N, NO_3^--N, DO, and PO_4^{3-}. Factor 3, contributing 10.31% of the variance, was correlated with temperature, pH, and Fe. Factor 4, which accounted for 9.52% of the variance, had high loadings for TSS and NO_2^-. Factor 5, explaining 8.67% of the variance, was associated primarily with Log(coliform).

2) Surface water quality index

The WQI demonstrated notable spatial and temporal variations in the study area (Figure 2). During the dry season, the water quality in the headwater area is moderate, with a WQI value of 0.5 [24]. In contrast, in the city area, it was higher at 0.56, but the results showed no significant difference. Similarly, in the rainy season, the WQI was 0.52 in the headwater area and increased to 0.60 in the city area, indicating a consistent spatial trend of higher water quality ($p < 0.05$). Temporally, the WQI in both areas improved during the rainy season, with the headwater WQI increasing from 0.50 to 0.52 and the city WQI increasing from 0.56 to 0.60.

3) Water quality parameters in the two zones and two seasons

3.1) Spatial classification of monitoring site characteristics

The PCA/FA results revealed that the water quality parameters were influenced by five principal factors (Table 2), each of which exhibited distinct variations across spatial and temporal dimensions. Factor 1, which encompassed organic pollution indicators, demonstrated that BOD_5 concentrations ranged from 11.77 to 17.03 mg L^{-1}. Research results show that BOD_5 values in the rainy season are higher than those in the dry season. Significant spatial variation was observed, with BOD_5 levels in urban areas being consistently higher than those in headwater-stream regions during both the dry and rainy seasons, as evidenced by statistically significant differences (Figure 3a). Similarly, the COD concentrations ranged from 20.40 to 26.27 mg L^{-1}, with values in the rainy season being higher than those in the dry season. Higher COD values were consistently recorded in urban areas than in headwater-stream locations across both seasons, with statistically significant differences (Figure 3b).

For Factor 2, the results revealed that the NH_4^+-N concentrations ranged from 0.11 to 0.32 mg L^{-1}, with the highest value recorded in the city during the dry season, indicating a statistically significant difference ($p < 0.05$) (Figure 4a). A similar pattern was observed for NO_3^--N, with concentrations ranging from 0.24 to 0.71 mg L^{-1}, and the highest NO_3^--N level also occurred in the city during the rainy season, with a statistically significant difference ($p < 0.05$) (Figure 4b). In contrast, the DO concentrations ranged from 5.97 to 6.75 mg L^{-1}, with the highest DO level observed in the headwater–stream area during the dry season, which was significantly different from that in other areas ($p < 0.05$) (Figure 4c). For PO_4^{3-}, a trend similar to that of NH_4^+-N and NO_3^--N was observed, with the highest concentration recorded in the city during the rainy season, reaching 0.18 mg L^{-1}, significantly different from that in other areas ($p < 0.05$) (Figure 4d).

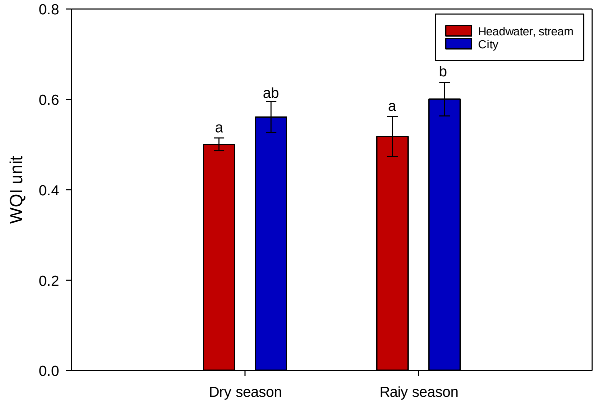

Figure 2 Water quality index of spatial and temporal variations in this study. The data are presented as the means±standard deviations; different letters indicate significant differences according to ANOVA and Tukey's HSD test (p <0.05).

Table 2 Loading values of 12 water quality parameters from principal component analysis/factor analysis

Water parameters	F actor 1	Factor 2	Factor 3	Factor 4	Factor 5	Parameter weightage
BOD_5	**0.950**	0.227	-0.037	-0.003	0.037	0.107
COD	**0.949**	0.227	-0.052	0.010	0.054	0.107
NH_4^+-N	0.203	**0.745**	-0.083	-0.095	-0.090	0.075
NO_3^--N	0.398	**0.687**	-0.115	-0.021	0.086	0.075
DO	0.045	**-0.636**	0.398	-0.073	-0.199	0.075
PO_4^{3-}	0.186	**0.596**	0.336	0.010	-0.205	0.075
Temperature	0.047	-0.206	**0.689**	-0.026	-0.282	0.072
pH	-0.003	-0.141	**0.647**	-0.148	0.320	0.072
Fe	-0.204	0.143	**0.577**	0.130	0.182	0.072
TSS	0.020	-0.253	0.002	**0.775**	0.147	0.087
NO_2^-	-0.016	0.165	-0.027	**0.768**	-0.166	0.087
Coliform	0.088	-0.023	0.088	-0.021	**0.858**	0.096
Eigenvalue	3.057	1.558	1.237	1.142	1.041	
Percentage	25.478	12.983	10.306	9.516	8.671	
Cumulative percentage	25.478	38.462	48.767	58.283	66.955	
Factor weightage	0.381	0.194	0.154	0.142	0.13	

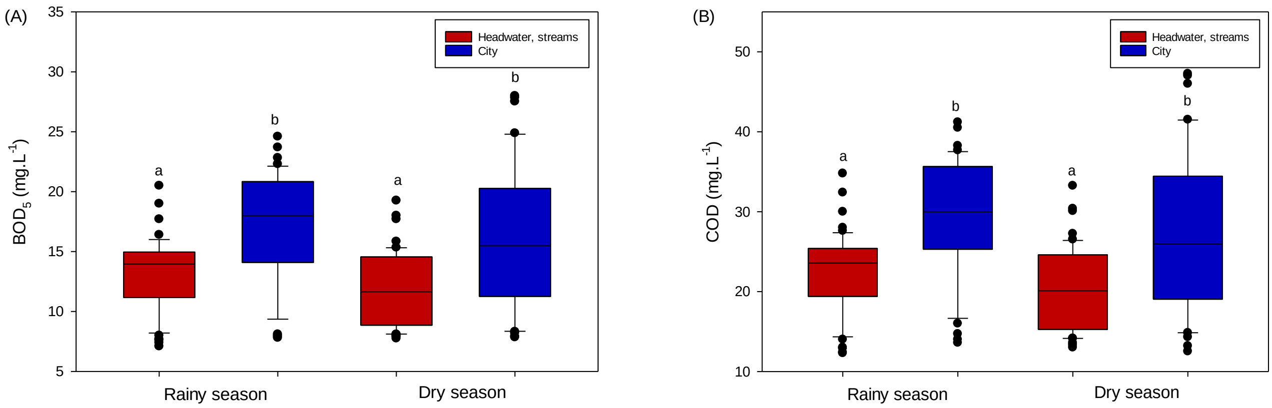

Figure 3 The water quality parameters for factor 1, including (A) BOD_5 and (B) COD, are affected by the headwater and city conditions in the dry and rainy seasons. The data are presented as the means±standard deviations, and different letters indicate significant differences according to ANOVA and Tukey's HSD test (p <0.05).

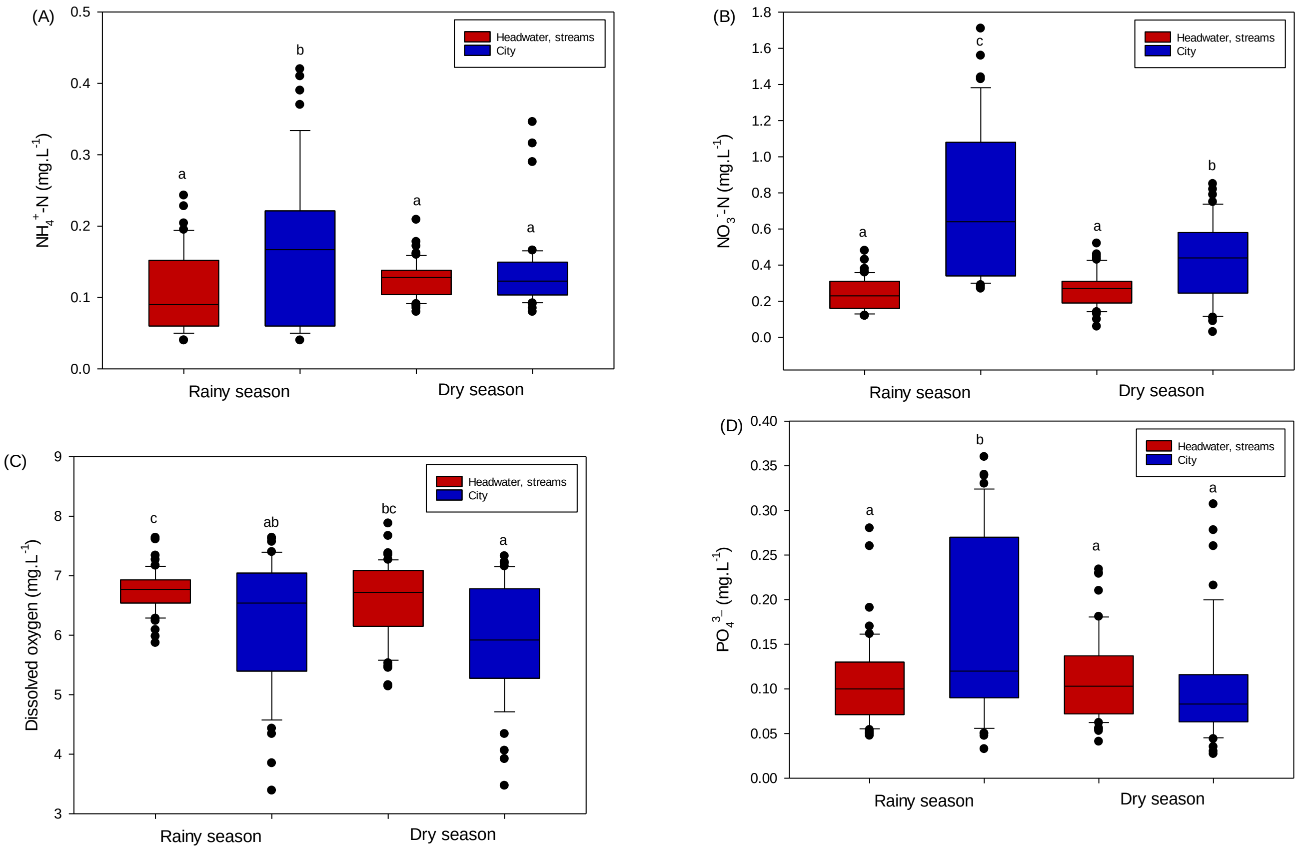

Figure 4 The water quality parameters for factor 2 are affected by the headwater and city during the dry and rainy seasons and include (A) NH_4^+-N; (B) NO_3^--N; (C) DO; and (D) PO_4^{3-}. The data are presented as the means±standard deviations, and different letters indicate significant differences according to ANOVA and Tukey's HSD test ($p < 0.05$).

For Factor 3, the temperature across the study sites ranged from 28.98 to 29.34°C, showing no statistically significant difference among the locations (Figure 5A). The pH values ranged from 7.00 to 7.20, with the highest value observed in the headwater–stream area during the dry season (Figure 5B). The Fe concentrations varied from 0.72 to 1.13 mg L^{-1}, with the highest concentration recorded in the headwater–stream area during the dry season (Figure 5C). Factor 4 demonstrated a strong correlation with the TSS and NO_2^-. The TSS concentrations ranged from 41.69 to 67.01 mg L^{-1}, with the highest TSS levels observed in the headwater–stream area, which were significantly higher than those in the city area (Figure 5D). The NO_2^- concentrations ranged from 0.02 to 0.03 mg L^{-1}, with the highest concentration recorded in the city during the rainy season (Figure 5E). For Factor 5, represented solely by log(coliform), the values ranged from 3.21 to 3.24 across the study areas, with no statistically significant difference detected between the locations (Figure 5F).

3.2) Sensitivity analysis for percentage contribution and source apportionment

The multivariable regression analysis revealed that WQI was significantly correlated with all five factors extracted from the PCA/FA analysis, with factors 1, 2, 3, 4, and 5 accounting for 47.61%, 26.04%, 11.21%, 9.43%, and 5.69% of the total variance in the WQI index, respectively (Table 3). All five factors together accounted for 99.80% of the total variance in the WQI.

Table 3 Percentage of individual latent factors from PCA/ FA in explaining the total variance of WQI in this study

Latent factor	Percentage (%)	Prob > F	Influenced parameters	Pollution source
Factor 1	47.61	< 0.0001	BOD_5, COD	Residential activities
Factor 2	26.04	< 0.0001	NH_4^+-N, NO_3^-–N, DO, PO_4^{3-}	Agricultural activities
Factor 3	11.21	< 0.0001	Temperature, pH, Fe	Mixed sources
Factor 4	9.43	< 0.0001	TSS, NO_2^-	Aquatic contaminants
Factor 5	5.69	< 0.0001	Log(coliform)	Domestic wastewater and livestock activities
Error	0.02			
Total variance	100.0			

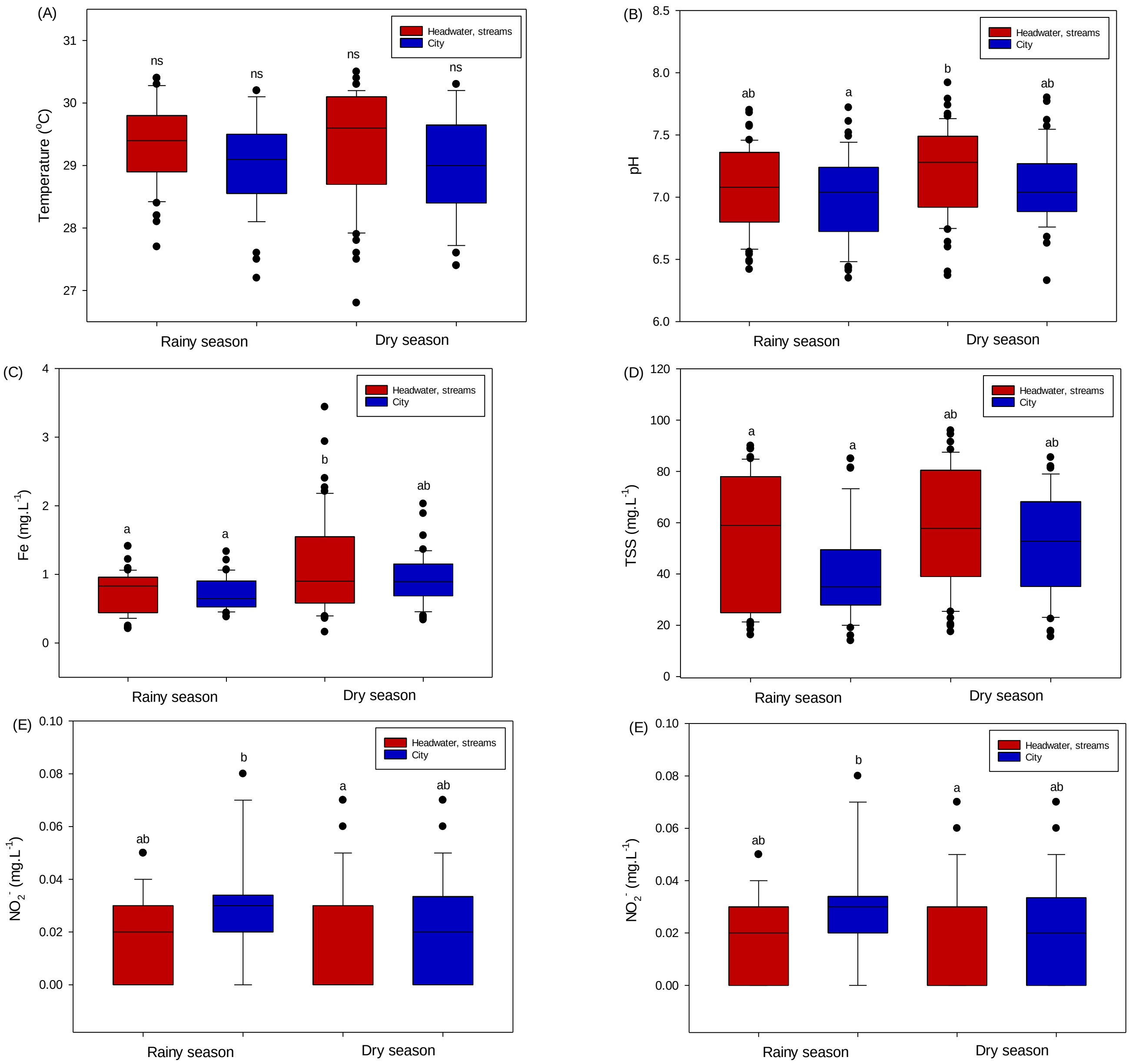

Figure 5 The water quality parameters for factor 3 include (A) temperature, (B) pH, and (C) Fe; those for factor 4 include (D) TSS and (E) NO_2^-; and those for factor 5 include Log(coliform) (F), which are affected by the headwater and city in the dry and rainy seasons. The data are presented as the means±standard deviations, and different letters indicate significant differences according to ANOVA and Tukey's HSD test ($p < 0.05$).

3.3) Hierarchical agglomerative cluster analysis of short-term spatiotemporal water quality patterns

To elucidate spatial and temporal patterns in surface water quality, hierarchical agglomerative cluster analysis (HACA) was applied to the standardized values of the water quality index and twelve measured parameters across 36 sampling sites. Using Ward's linkage and Euclidean distance, separate dendrograms were generated for the dry (Figure 6A) and rainy (Figure 6B) seasons, and clusters were delineated at a 60% similarity threshold to identify segments of differing vulnerability and to pinpoint statistically redundant stations.

During the dry season, two principal clusters emerged. Cluster I comprised 12 headwater/stream sites and was typified by low organic load, minimal nutrient concentrations, high dissolved oxygen, neutral pH, low TSS, low iron and minimal coliform counts, reflecting limited anthropogenic disturbance under base-flow conditions. In contrast, Cluster II grouped the remaining 24 sites predominantly within the urban/city reach and was characterized by elevated BOD_5 and COD, higher nutrient levels, reduced DO, increased TSS, elevated coliform counts and higher iron concentrations. Tightly linked station pairs (e.g., S13–S16; S21–S28) exhibited nearly identical profiles, indicating candidates for de-selection without compromising network representativeness.

Under rainy-season conditions, three distinct clusters were identified. Cluster I (28 sites) spanned headwater areas to peripheral urban areas and presented moderate increases in organic and nutrient loads, along with elevated coliform counts, attributable to diffuse runoff. Cluster II (four sites: S15–S17 in the headwater reach and S26 in the city) presented the highest turbidity and nutrient spikes, indicating localized stormwater discharge and soil erosion hotspots. Cluster III, comprising site S35 alone, maintained the highest iron and coliform levels under flood conditions, highlighting its unique vulnerability to urban-estuarine influences.

3.4) Pearson correlation between water parameters and the water quality index

The correlation analysis of the water quality parameters revealed significant interrelationships and their respective influences on the WQI (Figure 6). Among the organic pollution indicators, BOD_5 and COD exhibited robust positive correlations ($r = 0.99$, $p < 0.05$). The WQI was negatively correlated with both parameters ($r = -0.46$ for BOD and $r = -0.40$ for COD), indicating their adverse impact on water quality.

The nutrient parameters showed notable correlations that highlighted their influence on water quality. Ammonium (NH_4^+) exhibited a moderate positive correlation with NO_3^- ($r = 0.55$), suggesting common pollution sources, likely from agricultural runoff or wastewater discharge. NH_4^+ also had a moderately negative relationship with DO ($r = -0.34$), which shows that nutrient enrichment reduces oxygen levels, which is a sign of eutrophication. Nitrate ($NO3^-$) also had a weak relationship with organic pollution markers such as BOD_9 and COD ($r = 0.48$ for both), which shows that nutrients affect the breakdown of organic matter. Phosphate (PO_4^{3-}), however, was weakly correlated with the other parameters and showed no significant direct relationship with the WQI.

The WQI and DO were positively correlated ($r = 0.35$), highlighting the importance of DO in maintaining good water quality. As expected, DO showed moderate negative correlations with BOD_5 ($r = -0.34$) and COD ($r = -0.31$), reflecting the oxygen consumption required for the breakdown of organic matter. These findings confirm the critical role of DO as a key indicator of aquatic ecosystem health.

TSS exhibited weak positive correlations with COD ($r = 0.25$) and Fe ($r = 0.22$), suggesting its association with particulate pollution and sediment-bound metal inputs. Similarly, Fe demonstrated a moderate positive correlation with WQI ($r = 0.77$), indicating that higher concentrations of Fe in this study were not necessarily detrimental to water quality. The log(coliform), the pathogenic indicator, exhibited weak or negligible correlations with most other parameters, indicating that organic or nutrient pollution did not influence its variability. The physical parameters, such as temperature and pH, also displayed weak or negligible correlations with the WQI and other parameters, indicating limited influence from seasonal or anthropogenic factors in this dataset.

Discussion

This study extracted five main factors from the PCA/FA analysis (Table 2). Moreover, five primary pollution sources were identified as having the most significant impact on 12 surface water quality parameters in the study area. Among the determining factors, the two most important pollution sources, BOD_5 and COD, are associated primarily with human activities, such as domestic wastewater and wastewater from agricultural and aquaculture areas. For example, agricultural production activities that utilize organic fertilizers release large amounts of organic matter into the environment [29]. Similarly, domestic wastewater contributes substantial nutrients (BOD_5) and organic matter (COD) along with sediment to surface water sources [30]. Additionally, inland and coastal aquaculture wastewater generates significant amounts of nutrients (BOD_5) and organic matter (COD) due to excess feed and waste from aquaculture activities [31]. Both the BOD_5 and COD levels exceeded the allowable limits set by the National Technical Regulation on the Surface Water Quality of Vietnam, level B, with threshold values of 6 mg L^{-1} and 15 mg L^{-1}, respectively [15]. Moreover, BOD_5 levels were also found to exceed the WHO (2006) [32] allowable limit (5 mg L^{-1}). These findings indicate that the water quality in the study area is polluted with organic matter.

The parameters NH_4^+-N, NO_3^--N, DO, and PO_4^{3-} presented high loading values for factor 2, suggesting that pollution originated from organic matter and nutrients linked to agricultural, forestry, and fishery production activities, as well as industrial, residential, and service sectors [33]. These sources often act synergistically to contribute to water pollution. For example, wastewater from agricultural and residential areas can release large amounts of phosphorus (P) into the environment [34]. Domestic wastewater contains high levels of phosphorus compounds [35]. With respect to DO, NH_4^+, and NO_3^-, domestic and livestock wastewater contains elevated levels of nutrients and organic matter [36]. Runoff from villages, gardens, and agricultural fields can transport residual fertilizers (nitrogen, phosphorus, and organic fertilizers) and pesticides into water sources [37–38]. This runoff increases the levels of NH_4^+, NO_3^-, P, nutrients, and organic matter in surface water, reducing DO levels and contributing to eutrophication and toxic algal blooms. Elevated concentrations of NH_4^+ and NO_3^- further decrease DO through increased BOD during oxidation–reduction processes involving algae and bacteria [39]. Nitrogen levels in surface water may originate from diverse sources, including atmospheric deposition, rainwater contaminants, agricultural runoff, domestic wastewater, and industrial effluents [40]. However, the most significant contributor is excess feed from aquaculture activities [31]. The concentrations of NH_4^+ in this study exceeded the limits established by the National Technical Regulation on the Surface Water Quality of Vietnam (> 0.3 mg L^{-1}), indicating nutrient pollution in the surface water. The results of the present study indicate that the NO_3^- concentration is consistent with the WHO (2018) [41] allowable level for drinking water quality of 50 mg L^{-1}. The DO concentrations also exceeded the limit of 5 mg L^{-1} specified in QCVN 08-MT:2023/BTNMT [15]. However, the DO levels in this study were higher than those reported in other regions, such as Kien Giang [42], Tra Vinh [42], Dong Thap [43], An Giang [44], and Can Tho [45]. The lower DO levels in An Giang and Can Tho have been attributed to biodegradable substances and fertilizers from agricultural lands [45]. While DO may not directly threaten human health, it can influence the chemical properties of water, including the behavior of other compounds [46].

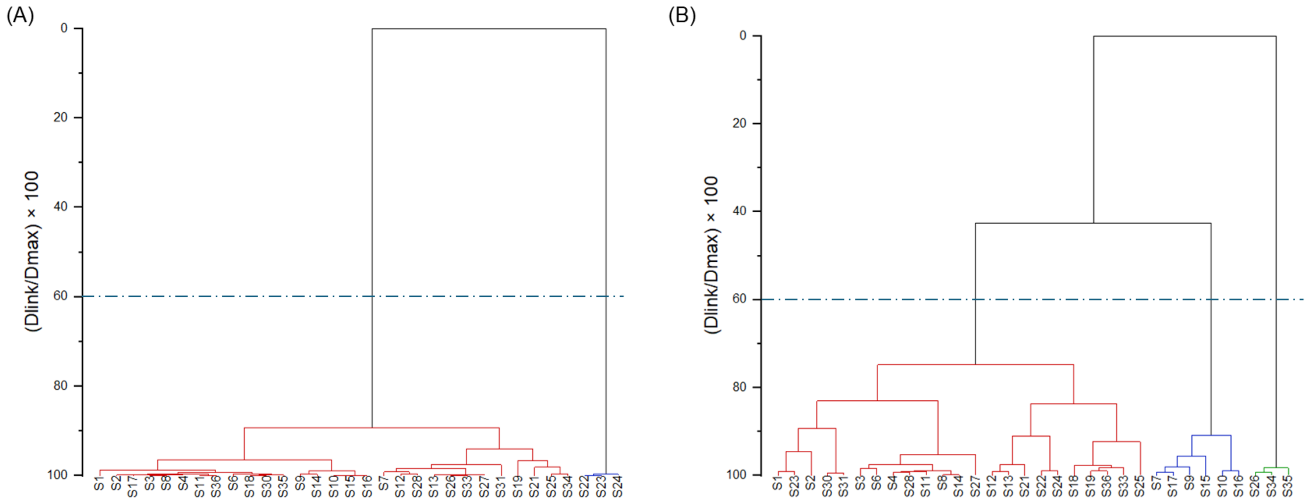

Figure 6 Dendrograms showing clustering of sampling sites according to surface water quality characteristics of the sampling sites in Tre Province during the (a) dry and (b) rainy seasons.

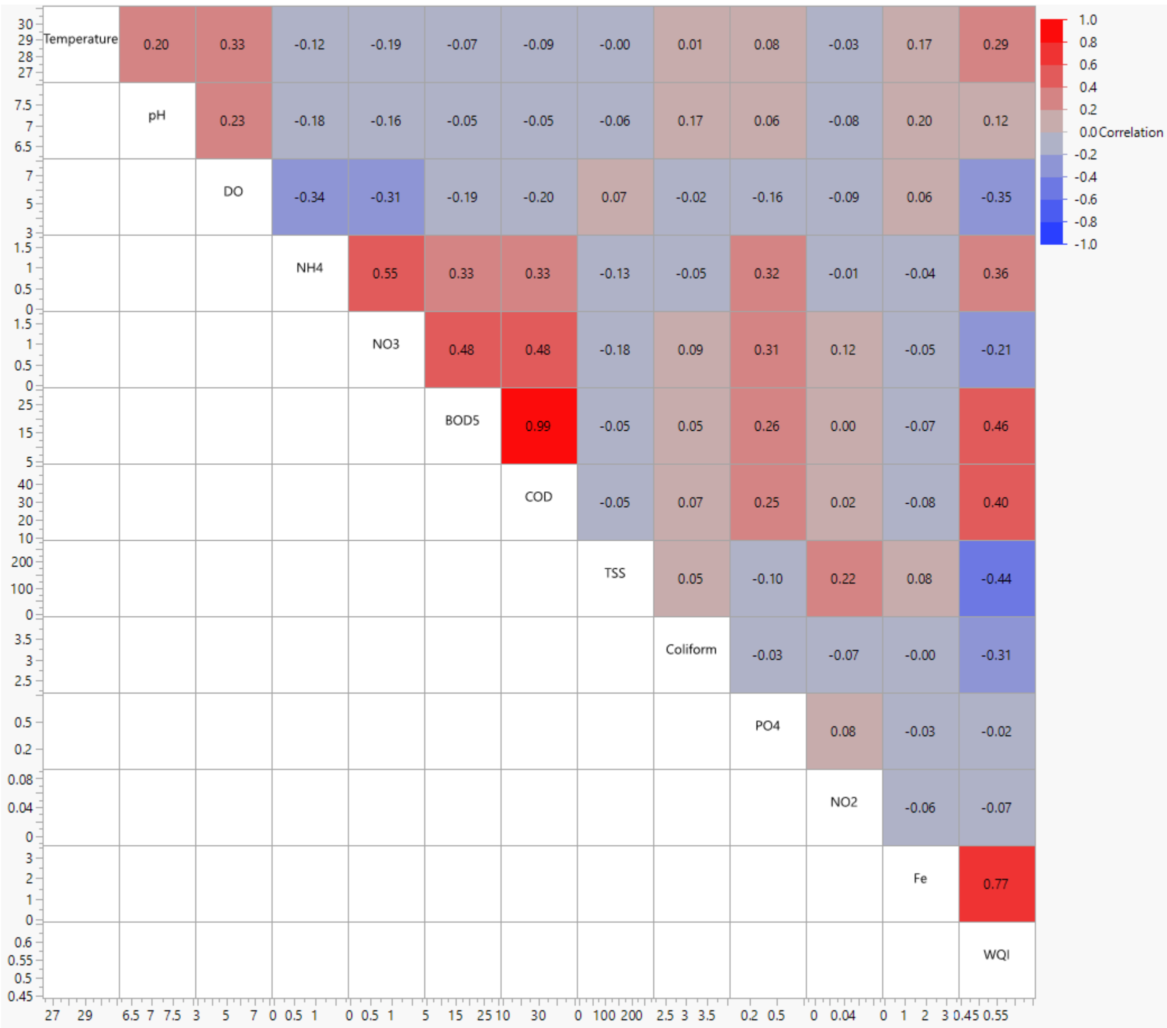

Figure 7 Pearson correlation analysis between water parameters and the water quality index.

According to the National Technical Regulation on Surface Water Quality of Vietnam, the pH limit value is 6.0–8.5, indicating that the water quality of the study area is in accordance with current standards [15]. Moreover, the pH of the river water in this study fell within the permissible limits set by the WHO (2022) [47] (usually in the range of 6.5–8.5), indicating slightly alkaline conditions. The pH of river water is influenced primarily by the local geology and buffering capacity of the water [48]. pH significantly impacts water quality by affecting hardness and alkalinity [49]. Water temperature is another critical parameter that influences river chemical and biological processes. Higher temperatures can accelerate the metabolic rates of aquatic organisms, increasing oxygen demand while simultaneously reducing oxygen solubility, which may lead to hypoxia [50]. These two elements, pH, temperature, and Fe, presented high loading values for factor 3, suggesting a mixed pollution source. Fe pollution is likely due to the leaching of iron sulfide alum in agricultural land used for rice production and aquaculture [51]. It occurs naturally in fresh water at concentrations ranging from 0.5–50 mg L^{-1} [47]. According to WHO (2011) [52], iron levels above 0.3 mg L^{-1} can stain laundry and plumbing fixtures, whereas levels below this threshold are usually tasteless but may cause turbidity and discoloration. This indicates that the Fe content in the water in the study area exceeds WHO (2011) [52]. Runoff during the rainy season may also wash surface materials from cultivated land into surface water sources [53].

The TSS and NO_2^- parameters presented high loading values with factor 4 (Table 1), primarily due to human activities in the study area, including domestic wastewater discharge, aquaculture, freight transport on rivers and at sea, and the natural characteristics of the Mekong River, which transports high levels of sediment [54]. Domestic wastewater contributes significant amounts of suspended solids and sediment to surface water sources [55]. Additionally, excess feed, waste, and metabolic byproducts from aquaculture activities can increase the amount of suspended solids in surface water [56–57].

According to the limits specified in the National Technical Regulation on Surface Water Quality of Vietnam, level B TSS levels in this study exceeded the prescribed limit (>15 mg L^{-1}) [15]. However, the TSS concentrations were lower than those reported in previous studies in canals and rivers in Kien Giang [42], Tra Vinh [42], Dong Thap [43], An Giang [44], and Can Tho [45]. High TSS levels increase water treatment costs and negatively impact the aquatic environment, making it less suitable for aquatic life. Nitrite (NO_2^-) is a product of nitrification and denitrification processes and can be toxic to aquatic organisms at concentrations lower than 0.1 mg L^{-1} [43]. Water containing NO_2^- is also a significant concern for human health, as it can cause methemoglobinemia or cyanosis by limiting oxygen transport in the blood [58]. However, in this study, the N-NO_2^- concentrations were within allowable limits and posed no toxicity risks to aquatic organisms or humans.

The coliform parameter had a high loading value with a factor of 5. According to the National Technical Regulation on Surface Water Quality of Vietnam, level B coliform density in the study area remains within permissible limits (<5,000 MPN per 100 mL) [15]. Additionally, the coliform density in this study was significantly lower than the levels reported in Kien Giang [42], Tra Vinh [42], Dong Thap [43], An Giang [44], and Can Tho [45]. This suggests that Tra Vinh Province has better control over coliform pollution than Dong Thap, An Giang, and Can Tho. Pollution sources in these areas predominantly originate from artificial waste, such as point sources (domestic, industrial, and aquaculture) and nonpoint sources (soil runoff and grazing), along with environmental factors such as temperature, pH, salinity, turbidity, nutrients, and hydrological regimes [59].

In this study, HACAof twelve water quality parameters across headwater (S1–S18) and urban (S19–S36) reaches revealed two clusters in the dry season and three clusters in the rainy season, highlighting the dual influence of baseflow dilution and monsoonal runoff on spatial heterogeneity in water quality. Moreover, tightly linked station pairs identified by the dendrograms denote opportunities for network optimization through the de-selection of statistically redundant sites. The transition from two to three clusters between the dry and rainy seasons reflects the concentration dilution dynamics common to fluvial systems under alternating hydrological regimes. Specifically, during low-flow periods, reduced runoff leads to the accumulation of both point and diffuse contaminants, whereas the onset of rainfall mobilizes both stored pollutants and upland sediments, thereby increasing spatial variability [60–63]. This pattern parallels findings in other monsoon-influenced catchments, where diffuse agricultural inputs increase nutrient and organic matter loads during wet periods, resulting in finer cluster differentiation [64–67]. Consistent with previous riverine HACA applications, headwater sites (Cluster I in the dry season) presented low BOD_5, COD and nutrient concentrations, indicative of minimal anthropogenic impact. In contrast, urban clusters presented elevated BOD_5, COD, NH_4^+–N and coliform counts, reflecting combined sewage and stormwater inputs.

The PCA/FA analysis results for the water parameters were used to calculate the WQI. The WQI for urban areas was higher than that for headwater streams, indicating better water quality in city regions. Overall, the PCA/FA analysis highlighted that, under the current conditions in Ben Tre Province, the primary sources of surface water pollution are waste generated from agricultural and fishery production, industrial activities, services, and residential areas. The implementation of best management practices, such as correctly timed fertilizer application, controlled irrigation, contour plowing, and establishing buffer zones, is crucial for mitigating pollution from agricultural production. However, controlling pollution sources from upstream agricultural areas far from rivers remains challenging. This situation is not unique to the Mekong River but is common in many international river systems where pollutants from distant agricultural areas are transported downstream during the rainy season. Addressing such pollution requires coordinated efforts among sectors and neighboring countries to monitor and manage agricultural areas. Improving the water quality of coastal rivers requires a comprehensive approach that addresses seawater intrusion, agricultural runoff, and domestic pollution sources. Management strategies should account for seasonal variations and the characteristics of each pollution source. Although this study provides valuable insights, it has certain limitations. A larger dataset must be collected and analyzed to draw more comprehensive conclusions about natural water quality trends.

Conclusion

Over two years, this study assessed surface water quality in Ben Tre Province, Vietnam, identifying five key pollution factors that explained 66.95% of the total variance in water quality parameters. Organic pollution (BOD_5 and COD) and nutrient pollution (NH_4^+-N, NO_3^--N, and PO_4^{3-}) were the most significant contributors, largely driven by domestic wastewater, agricultural runoff, and aquaculture activities. The WQI showed spatial and temporal variations, with a trend of higher water quality in urban areas than in headwater regions and slight improvements during the rainy season. Correlation analysis further emphasized the strong relationships between these pollutants and water quality, with BOD_5 and COD showing a significant negative correlation with WQI, underscoring the impact of organic pollution on water quality degradation. Seasonal and spatial analyses revealed slightly better water quality in urban areas than in headwater streams, with improvements observed during the rainy season. Despite these seasonal variations, many parameters, including nitrogen compounds and coliforms, exceeded national standards, highlighting persistent pollution challenges. Multivariable regression linked Factor 1 predominantly to residential wastewater and aquaculture effluents (BOD_5, COD), Factor 2 to agricultural runoff and fertilizer application (NH_4^+–N, NO_3^-–N, PO_4^{3-}–P, DO), Factor 3 to mixed sources, including groundwater–surface water interactions (temperature, pH, Fe), Factor 4 to soil erosion and pond discharges (TSS, NO_2^-), and Factor 5 to domestic sewage and livestock operations (coliform). Hierarchical agglomerative cluster analysis further separated low-impact headwater reaches from urban segments with site S35, reflecting combined estuarine saline intrusion and urban effluent pressures, and identified redundant station pairs (e.g., S13–S16) for potential network optimization. To address these issues, implementing feasible strategies and policies for managing, regulating, and treating primary pollution sources is vital, thereby ensuring a healthier environment and supporting the sustainable development of Ben Tre Province.

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