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Original Article

Apply Multivariate Statistical Analyses to Assess Surface Water Quality in the Quang Binh River System

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Abstract: This paper applies multivariate statistical analyses to identify the key factors influencing surface water quality during the socio-economic development period 2016-2020 in Quang Binh Province. A comprehensive water quality dataset, comprising ten parameters across 15 locations of the Quang Binh River system, was collected four times per year. Socioeconomic data, including population density, aquaculture land area, agricultural production land area, forestry land area, the number of farms, the number of enterprises engaged in production, and business activities, were collected from administrative units within the monitoring area. The factor analysis using the principal component method identified two main components that explain around 57.82% of the total variance. Based on the loading values of the variables, these components were interpreted as representing anthropogenic and natural-environmental influences. The cluster analysis of socio-economic development conditions identified three distinct regions: urban areas, coastal rural areas, and mountainous rural areas. The results of the study of variance using one-way ANOVA demonstrated the impact of socio-economic indicators on the differentiation of environmental characteristics of water quality in rivers (coliform, BOD_5, COD, and $N\text{-}NH_4^+$), with statistically significant differences ($p < 0.05$). This study highlights the practical application of multivariate statistical techniques in informing decision-makers involved in environmental quality monitoring in Quang Binh province, thereby providing actionable insights for effective environmental management and policy development.

Keywords: Surface water quality, factor analysis, cluster analysis, ANOVA, Quang Binh.

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1. Introduction

Water is an essential resource for human and ecosystem survival; however, water security is becoming a severe challenge globally due to industrialization, rapid urbanization, global population growth, climate change, and economic activities [1-3]. The quality of river water surfaces is affected by numerous natural factors, and anthropogenic factors [4, 5] pose a significant challenge in reducing pollutants. With the characteristics of river surface water consisting of primary and secondary streams, surface water quality is subject to complex spatial and temporal variations that are often difficult to interpret [5]. Recent studies have demonstrated the effectiveness of multivariate statistical methods, such as cluster analysis (CA), principal component analysis (PCA), and factor analysis (FA), in analyzing complex water quality datasets, identifying pollution sources, and understanding spatiotemporal variations, thereby supporting regional water quality management strategies [2, 3, 5-7]. The dense river system with the five main river basins - Roon, Gianh, Ly Hoa, Dinh, and Nhat Le of Quang Binh province, is characterized by short and step rivers originating from the Truong Son mountain range and flowing into the East Sea through estuaries, plays a crucial role in regulating and supplying water resources to a population exceeding 900,000 inhabitants. Rapid economic development has placed significant pressure on water resources, including wastewater from industrial zones, craft villages, river sand mining, and agricultural runoff, which collectively contribute to the degradation of water quality. However, limited research has been conducted to link changes in water quality to socioeconomic activities in this region [7, 8].

Recent research has highlighted the significant impact of socioeconomic development on surface water quality, primarily through agricultural runoff, domestic wastewater, and industrial discharges [2, 3, 6, 7, 9, 10]. However, few studies have applied multivariate statistical techniques to identify key drivers of water quality in provincial river systems, leaving a gap in understanding the relationships between socio-economic activities and environmental impacts in Quang Binh Province.

This study addresses these gaps by applying multivariate statistical techniques to assess surface water quality in Quang Binh Province from 2016 to 2020, integrating socio-economic data with water quality parameters. The study's findings offer policymakers valuable insights and provide a foundation for targeted interventions, enhanced monitoring, and sustainable water resource management strategies.

2. Material and Methods

2.1. Data

The water dataset underwent collection in four annual instances spanning from 2016 to 2020, encompassing two periods within the dry season (Phase I: late February to early March, Phase II: late April to early May) and two periods within the rainy season (Phase III: late July to early August, Phase IV: late October to early November).

Table 1. Information on water surface sampling sites

River	Name sample	District
Roon	M_1	Quang Trach
Gianh	M_2 M_3	Tuyen Hoa Bo Trach
Ly Hoa	M_4, M_5, M_6	Bo Trach
Dinh	M_6,M_7, M_8	Bo Trach
Nhat Le	M_9, M_{10}	Quang Ninh Dong Hoi City
Kien Giang	M_{11}	Le Thuy
Dai Giang	M_{12}	Quang Ninh
My Duc	M_{13}	Le Thuy
Le Ky	M_{14}	Dong Hoi
Son	M_{15}	Bo Trach

A total of 15 water monitoring sites were selected, representing ten rivers across five districts (Le Thuy, Quang Ninh, Bo Trach, Quang Trach, Tuyen Hoa) and one city (Dong Hoi). The sites were chosen based on their locations along rivers and streams that receive wastewater from residential areas, craft villages, and industrial activities [8]. The locations of the sampling sites are illustrated in Figure 1 and listed in Table 1.

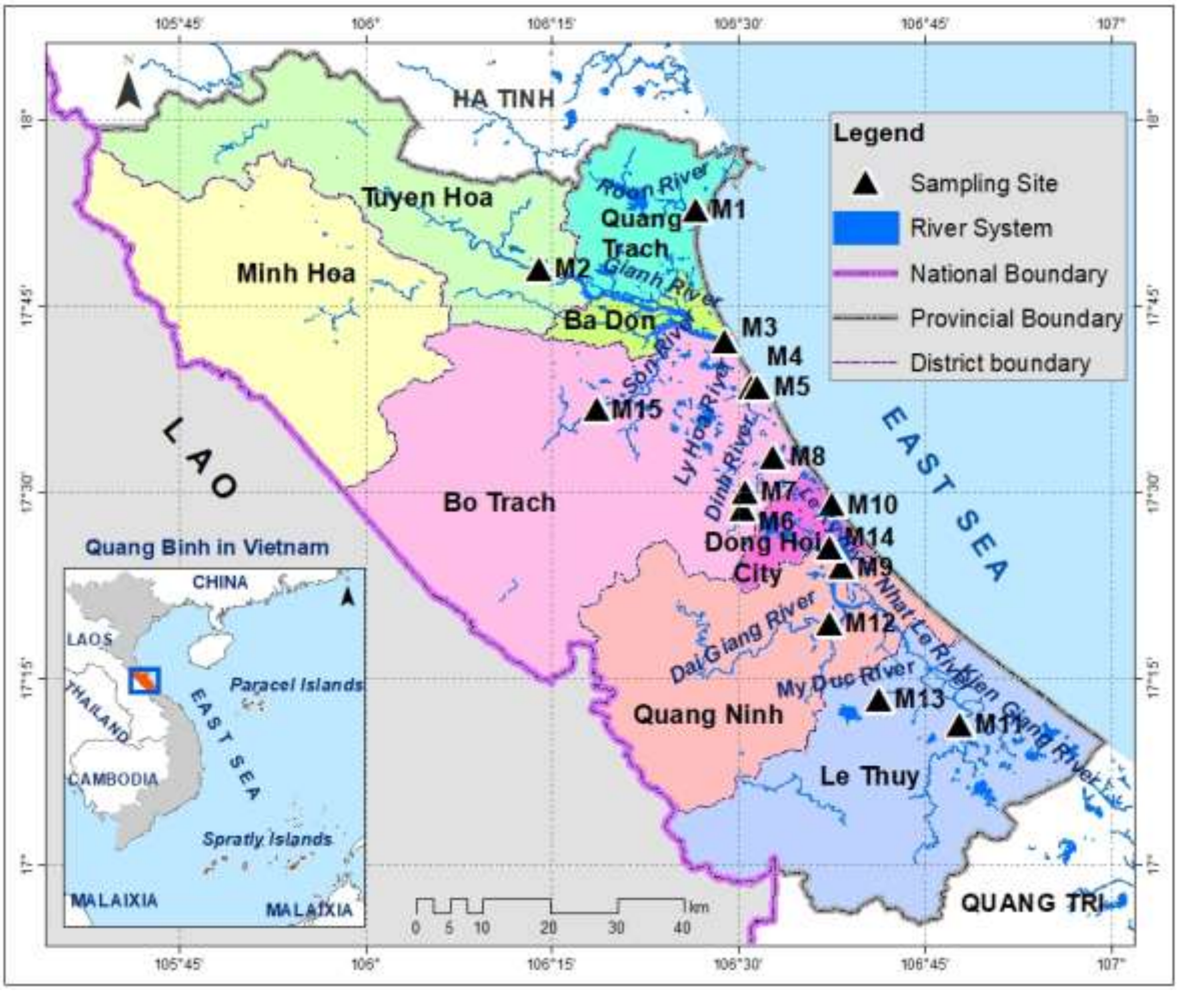

Figure 1. Location of the study area and sampling sites in Quang Binh River systems.

At designated monitoring points, water samples, upon retrieval, were analyzed using the method regulated by TCVN 6663-1:2011 (ISO 5667-1:2006). They were then preserved according to TCVN 6663-3:2021 (ISO 5667-3) and subsequently transported to the laboratory for analytical purposes [11, 12]. In situ measurements were conducted for pH, temperature, and dissolved oxygen (DO), while laboratory analysis, employing standard methods, determined the values for total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), ammoniacal nitrogen ($N\text{-}NH_4^+$), iron (Fe), phosphate ($P\text{-}PO_4^3$), and coliform.

Key variables used for cluster analysis included population density, aquaculture land area, agricultural production land area, forestry land area, number of farms, and number of enterprises engaged in production and business activities. These indicators were selected for their relevance to major socio-economic activities and land use patterns that influence surface water quality [13, 14]. Population density and the number of enterprises reflect urbanization and industrialization, often linked to increased domestic and industrial wastewater discharge. Aquaculture and agricultural areas contribute to nutrient and sediment loads through runoff containing fertilizers, feed, and organic waste. The number of farms serves as a proxy for livestock intensity, which can increase BOD_5 and coliform levels in nearby water bodies. Conversely, forestry land represents areas with limited human activity and is a comparative baseline. These variables were used to assess spatial variations in water quality in relation to socio-economic development (Appendix 1).

Socio-economic data were sourced from the Quang Binh Statistical Yearbooks (2016-2020), which provided district-level data for Quang Trach, Tuyen Hoa, Bo Trach, Quang Ninh, Dong Hoi, and Le Thuy [15].

2.2. Methods

A combination of descriptive and multivariate statistical methods was employed to examine spatial and temporal variations in surface water quality and to evaluate the influence of socio-economic development across the Quang Binh river system.

Box plots were used to visualize seasonal (dry and rainy seasons) and spatial patterns of water quality parameters, facilitating comparisons against the Vietnamese National Technical Regulation on Surface Water Quality (QCVN 08-MT:2015/BTNMT, type B1), which is applicable for irrigation purposes or other purposes with similar water quality requirements or uses as type B2 - water transportation and other purposes with low water quality requirements. Potential outliers were identified using the interquartile range (IQR) method as part of exploratory data analysis [16].

Multivariate statistical methods were applied to explore the relationships between water quality variables and socio-economic factors [2, 3, 5-7].

Prior to analysis, the suitability of the dataset was assessed using the Kaiser-Meyer-Olkin (KMO) test and Bartlett's Test of Sphericity. Factors with eigenvalues greater than one and cumulative explained variance of approximately 50–60% were retained. Factor loadings were interpreted after Varimax rotation, with values above 0.4 considered significant [17, 18].

Cluster Analysis (CA), using Ward's method, was performed to classify monitoring sites based on similar socio-economic development characteristics [2, 6].

Finally, a one-way Analysis of Variance (ANOVA) was conducted to examine differences in key water quality parameters identified through FA among the socio-economic clusters. This approach supports the study's aim of assessing how regional development patterns influence surface water quality across Quang Binh Province. All statistical calculations were performed by using Excel and SPSS software packages.

3. Results

3.1. Temporal and Spatial Variations in Water Quality Parameters from 2016 to 2020

Descriptive statistics (Table 2) indicated that the mean values of all water quality parameters fell within the permissible limits of QCVN 08-MT:2015/BTNMT (type B1) [16]. However, maximum concentrations of TSS, BOD_5, COD, $P–PO_4^{3-}$, and $N–NH_4^+$ exceeded regulatory thresholds during the study period, indicating the occurrence of periodic pollution events. The full statistical distribution by season is presented in Appendix 2. Figure 2 presents the seasonal and spatial distribution of key parameters. This comprehensive depiction highlights significant differences in water quality across time and space in the Quang Binh River system from 2016 to 2020.

Table 2. Descriptive statistics of variables during 2016-2020

Variables	Unit	Max	Min	Mean	Median	Std. Deviation	Vietnam regulations 2015 (B1)
pH	#	8.43	5.90	7.21	7.21	0.35	5.5-9.0
Temperature	°C	39.00	19.70	28.40	27.55	2.92	#
TSS	mg/l	57.00	5.00	12.00	15.54	9.38	50
DO	mg/l	9.35	4.45	6.82	6.84	0.49	≥ 4
BOD_5	mg/l	25.00	1.60	7.60	8.37	4.54	15
COD	mg/l	38.00	0.00	12.00	12.84	7.65	30
Fe	mg/l	1.17	0.00	0.05	0.12	0.20	1.5
$P\text{-}PO4^{3-}$	mg/l	0.84	0.01	0.05	0.06	0.08	0.3
$N\text{-}NH4^{+}$	mg/l	1.32	0.00	0.06	0.11	0.16	0.9
Coliform	MPN/100 ml	3900.00	2.00	440.00	818.08	840.85	7500

Note: The minimum values for COD and $N–NH_4^+$ were recorded as zero during statistical processing in SPSS because the observed concentrations were below the detection limits of the laboratory methods (e.g., COD < 5 mg/L; NH_4^+ < 0.025 mg/L). These zero values are used solely for analysis and visualization purposes and do not indicate the actual absence of these parameters in the environment.

Total Suspended Solids (TSS) ranged from 5 to 57 mg/L (mean: 12 mg/L), with higher variability and more outliers in the dry season. This pattern is attributed to runoff from agricultural, construction, and industrial activities. Spatially, elevated TSS levels were observed in the Ron and Ly Hoa Rivers, likely due to upstream sediment loading from urban and farming areas.

Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD) followed similar seasonal trends. Dry-season BOD_5 averaged 8.6 mg/L (max: 25 mg/L), while COD averaged 13 mg/L (max: 38 mg/L), often exceeding B1 standards in urban rivers like Gianh, Ly Hoa, and Ron. These values indicate persistent organic pollution, likely from domestic wastewater, small-scale industry, and runoff from surrounding land uses.

$P–PO_4^{3-}$ concentrations were slightly higher in the dry season, with the Ly Hoa and Kien Giang Rivers consistently showing elevated levels. This may result from nutrient accumulation during low flows and urban-agricultural nutrient inputs.

$N–NH_4^+$ exhibited more significant variability during the rainy season, with peaks reaching up to 1.32 mg/L. Runoff following heavy rains likely transported fertilizer and organic waste into rivers. Higher average values in the dry season- particularly in the Ly Hoa and Le Ky Rivers- suggest continuous pollution from agricultural and urban sources.

Seasonal differences in water quality reflect typical hydrological dynamics: the dry season is characterized by pollutant accumulation and reduced dilution, whereas the rainy season enhances flushing but may also mobilize contaminants.

Spatially, urban-affected rivers, such as Ly Hoa and Ron, consistently exhibited degraded water quality, whereas upstream or rural rivers, like Dinh and My Duc, showed relatively better conditions.

These findings reveal distinct spatiotemporal patterns in water quality across the Quang Binh River system, providing a basis for the multivariate analysis in Section 3.2, which further examines the factors influencing these patterns.

Some water quality values, particularly for COD and $N–NH_4^+$, were reported below the detection limits of the laboratory methods (e.g., COD < 5 mg/L, NH_4^+ < 0.025 mg/L). These values were recorded as zero for consistency in statistical processing using SPSS. As a result, some minimum values in the boxplots (Figure 2) appear near or at zero. These should be interpreted as below-detection-limit values, not as the complete absence of these substances. This ensures that statistical models can handle the data without introducing bias from undefined values. However, it's worth noting that this treatment assumes the values are negligible, which is reasonable given the clean river context, but this should be acknowledged as a limitation in this study.

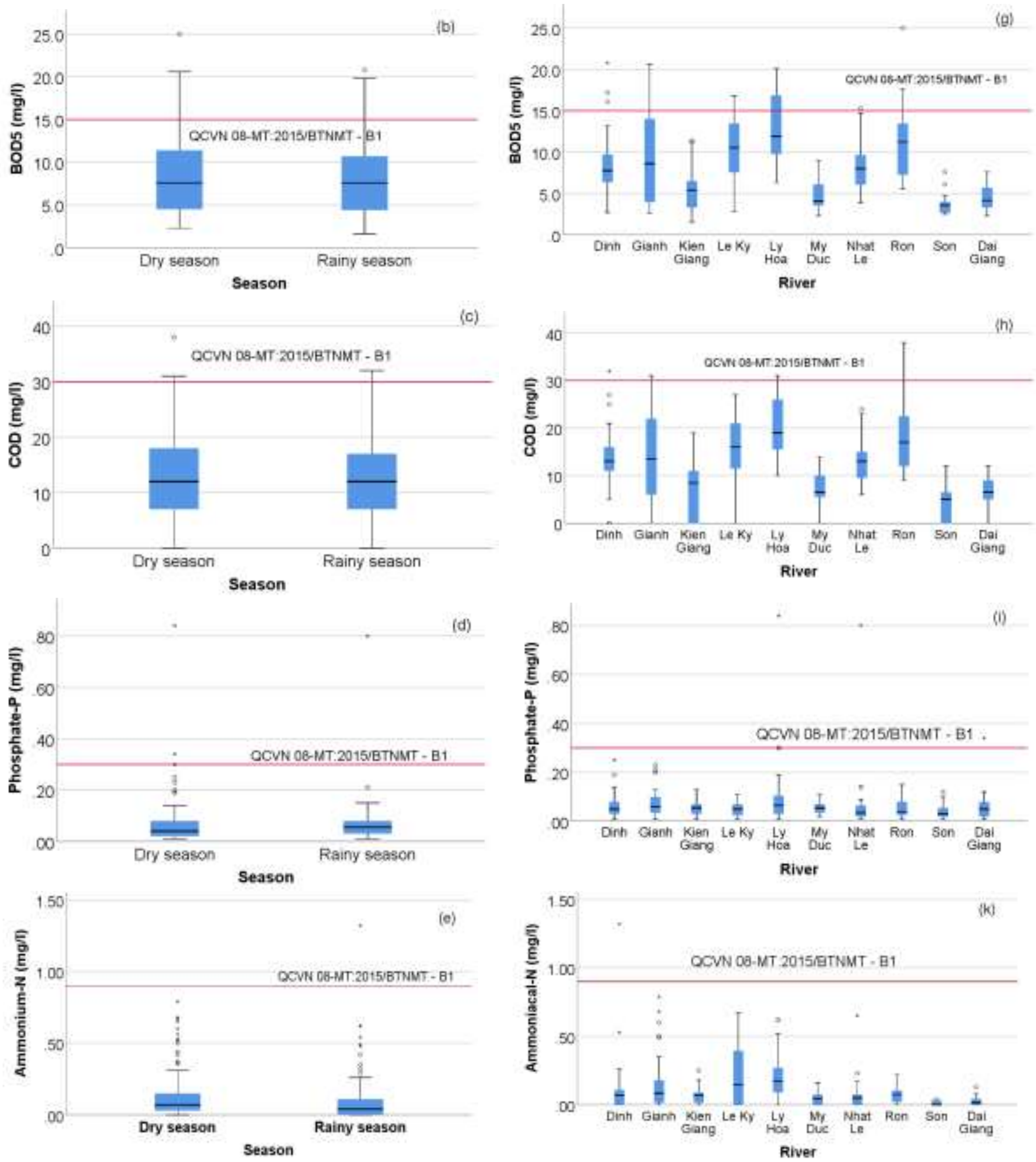

Figure 2. Characteristics of surface water quality in the Quang Binh river system from 2016-2020.

3.2. Factors Affecting Surface Water Quality

Principal Component Analysis (PCA) was conducted on the monitored dataset from 2016 to 2020 to explore the underlying factors influencing surface water quality. The Kaiser-Meyer-Olkin (KMO) value of 0.760 and a significant Bartlett's Test of Sphericity ($p < 0.05$) confirmed the dataset's suitability for factor analysis [11]. Variables with inadequate sampling adequacy, including temperature and Fe (diagonal values < 0.5 in the anti-image matrix), were excluded from the analysis [18].

PCA initially extracted multiple components; however, based on Kaiser's criterion (eigenvalues > 1), only the first two components were retained for interpretation. These two principal components accounted for 57.82% of the total variance, with PC1 contributing 43.59% and PC2 contributing 14.23% (Table 3). The remaining components, each explaining less than 10% of the variance, lacked interpretable loading structures and are summarized in Appendix 3. The factor loadings were interpreted based on a recommended absolute threshold of >0.4 for statistical significance [18].

Table 3. Factor loading for rotation factor matrix

Variables	Principal component (PC)	
	1	2
BOD_5	0.940	-0.133
COD	0.927	-0.114
Coliforms	0.840	-0.207
$N\text{-}NH_4^+$	0.715	-0.302
$P\text{-}PO4^{3-}$	0.349	0.073
pH	0.082	0.774
DO	-0.111	0.661
TSS	0.333	-0.457
Eigenvalues	3.487	1.138
% of Variance	43.59	14.23
Cumulative %	43.59	57.82

PC1 was strongly positively affected by BOD_5 (0.940), COD (0.927), and Coliform (0.840), moderately affected by $N\text{-}NH_4^+$ (0.715) with eigenvalue 3.487, explaining 43.59% of the total variance. The variables that cluster on the same factor suggest that PC1 is commonly associated with anthropogenic sources such as untreated domestic wastewater, livestock effluent, and agricultural runoff [19, 20]. Thus, PC1 was interpreted as a factor related to anthropogenic and organic pollution.

PC2 was defined by a strong loading for pH (0.774), a moderately favorable loading for dissolved oxygen (DO) (0.661), and a negative loading for total suspended solids (TSS) (–0.457), which could explain 14.23% of the total variance representing the effects of biological activity and environmental conditions. These variables indicate natural variability in water quality, which is linked to physicochemical conditions and ecological processes such as re-aeration, photosynthesis, water circulation, biological activity, and sediment transport [3, 18-20]. PC2 was, therefore, interpreted as a natural environmental factor.

The phosphate ($P\text{–}PO_4^{3-}$) variable, with a loading below the 0.4 threshold, was excluded from interpretation.

Identifying these two key components reflects distinct patterns in water quality variation across the study area. PC1 aligns with spatial patterns of pollution in rivers adjacent to urban and agricultural zones, whereas PC2 characterizes areas with more stable natural conditions. These findings align with the study's objective to discern the combined effects of socio-economic activities and environmental factors on river water quality in Quang Binh.

3.3. Relationship between Surface Water Quality and Socio-economic Development

CA has grouped districts by water sample sites into three groups based on their similarities and socioeconomic development characteristics, including demographic and agricultural activities, as shown in the Dendrogram classification tree (Figure 3). Surface water quality characteristics vary across groups of socio-economic development regions. Temperature, pH, TSS, DO, and $P\text{-}PO_4^{3-}$ are similar between regional groups. BOD_5 and COD have average values that gradually decrease from urban to coastal to mountainous regions, indicating that the pollution rate decreases from urban areas (characterized by high population density, a larger number of agricultural and aquaculture production, business enterprises, and a concentration of production establishments) to mountainous rural areas.

The one-way ANOVA analysis results of the factors extracted from factor analysis indicate that socio-economic development areas (urban, coastal rural, and mountainous rural) influence water surface quality. In particular, the parameters of the PC2 - the natural environmental factors (DO, pH)- did not differ between groups. These parameters are likely more stable and primarily affected by natural environmental conditions rather than human activities.

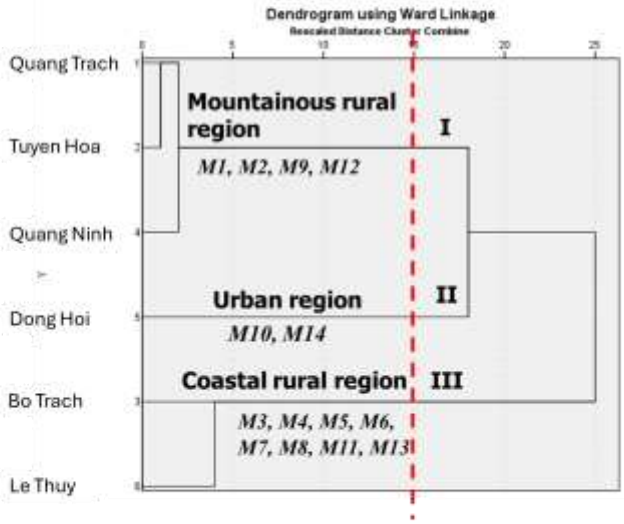

Figure 3. Clustering water quality monitoring sites in different socio-economic development regions.

Meanwhile, the water quality parameters of the anthropogenic activity factor (BOD_5, COD, Coliforms, Ammonia) differ significantly in the ANOVA test from the Control. Value Test of Homogeneity of Variances and Robust Tests of Equality of Means, giving values <0.05, confirming differences between regional groups (Table 4). The quality of water is significantly impacted by anthropogenic activities, such as population growth, agricultural production, and industrial activities, particularly in urban areas compared to rural and coastal regions.

Table 4. Oneway ANOVA analysis

	BOD_5	COD	Coliforms	Amoni
Test of Homogeneity of Variances				
Levene Statistics	3.824	4.509	16.852	8.142
Sig.	0.023	0.012	0.000	0.000
Robust Tests of Equality of Means				
Welch's Statistics*	4.982	5.342	17.961	11.304
Sig.	0.008	0.006	0.000	0.000

The results of in-depth ANOVA Post Hoc analysis also show that there is a significant difference between the average Coliform concentration between Group I (mountainous rural region) and Group II (urban area) with Mean difference = 394.683 (Sig. =0.03<0.05);

between Group III (coastal rural region) and Group II (urban region) where the Mean difference between as 513.233 (Sig. = 0.00<0.05). Urban regions (Group II) exhibit significantly higher coliform concentrations than rural and mountainous areas, indicating higher contamination from human and animal waste. This is likely due to high population density, inadequate sewage treatment, and more intensive agricultural practices in the urban and coastal areas of Quang Binh province.

Similarly, BOD_5 and COD also have relative differences between regional groups. The average difference between COD and BOD_5 between group I (mountainous rural region) and group II (urban area) is more significant than between group I (mountainous rural region) and group II (coastal rural region). The higher levels of BOD_5 and COD in urban areas indicate that organic pollution is more severe due to increased human activities, industrial waste, and untreated sewage. The mountainous areas have lower levels of organic pollution, likely due to fewer human activities and better water quality. The difference between the average ammonium content and the groups is relatively low, ranging from 0.6117 to 0.6589. This indicates that although ammonium levels differ slightly between regions, the impact of socio-economic activities on ammonium is less pronounced compared to BOD_5, COD, and coliforms. Ammonium may still originate from agricultural runoff or waste, but it appears to be less affected by the intensity of urban or rural activities.

4. Conclusion

This study examined water quality in Quang Binh's river systems over five years (2016-2020), utilizing data from 15 monitoring sites across 10 rivers. The robust dataset enabled the detection of long-term trends and geographic variations, essential for comprehensive water resource management.

Multivariate statistical techniques, particularly principal component analysis (PCA), identified two dominant factors affecting water quality. The first component was associated with organic and anthropogenic pollution, represented by high loadings of BOD_5, COD, coliforms, and ammonium. The second component reflected environmental and biological conditions, including pH, dissolved oxygen, and TSS. These findings suggest that both human activities and natural processes have a significant impact on surface water quality in the region.

Cluster analysis classified monitoring sites into three distinct socio-economic regions—urban, coastal, and mountainous rural—revealing spatial differentiation in pollution intensity. A one-way ANOVA confirmed significant differences in water quality parameters among these clusters, particularly in areas with higher population densities and industrial or agricultural activities.

These findings underscore the importance of integrating water quality monitoring with socioeconomic data to support evidence-based environmental management. Targeted actions, such as improving wastewater treatment in urban areas and promoting sustainable agricultural practices in rural regions, are recommended to mitigate anthropogenic impacts.

While this study provides valuable insights, it is limited by the use of secondary socioeconomic data and a constrained set of water quality parameters. Future work should incorporate more detailed industrial, land-use, and hydrological variables, as well as advanced modeling techniques, to better capture the complexity of water quality dynamics.

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