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Surface-Water Quality Assessment Across a River–Lagoon Continuum in Central Vietnam Using Parameter-Based Analysis, PCA, and VN_WQI

Environmental Significance Statement

Surface-water quality in tropical river–lagoon systems is shaped by strong seasonal forcing and localized human pressures, yet monitoring and management often remain fragmented. This study integrates parameter-based assessment, principal component analysis, and VN_WQI to evaluate water quality across the Huong River–Tam Giang lagoon continuum in Central Vietnam. The results show that deterioration is hotspot-driven and intensified during the rainy season rather than being uniform across the system. By identifying a reduced set of priority indicators and linking them to a policy-relevant water quality index, this work provides a practical basis for adaptive monitoring, more targeted pollution control, and improved water governance in vulnerable coastal communities.

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Surface-Water Quality Assessment Across a River–Lagoon Continuum in Central Vietnam Using Parameter-Based Analysis, PCA, and VN_WQI

Nguyen Dinh Phuoc[1,2,a], Le Trung Hieu[2,a], Hoang Thai Long[2], Nguyen Van Hop[2], Ho Xuan Anh Vu[2], Felix Bachofer[3], Dominic Sett[4], Nguyen Duc Cuong[5], Nguyen Dang Giang Chau[2]*

[1] Center for Natural Resources and Environment Monitoring, Hue City, Vietnam
[2] Department of Chemistry, University of Sciences, Hue University, Hue City, Vietnam
[3]DLR German Aerospace Center (DLR)—Earth Observation Center (EOC), Wessling, Germany
[4]United Nations University - Institute for Environment and Human Security (UNU-EHS), Bonn, Germany
[5] University of Education, Hue University, Hue City, Vietnam

[a] These authors share first authorship.
[*] Corresponding author: Nguyen Dang Giang Chau
e-mail: chaundg@hueuni.edu.vn
Address: Department of Chemistry, University of Sciences, Hue University, Nguyen Hue 77, Hue City, Vietnam,

ABSTRACT

This study assessed surface-water quality across a river–lagoon continuum in Central Vietnam using a framework of three modules: individual-parameter assessment, principal component analysis (PCA), and the Vietnam Water Quality Index (VN_WQI). Twelve monitoring campaigns were conducted from June 2022 to December 2023 at 20 sites covering the entire river–lagoon surface-water system, generating a dataset of 240 observations for 18 physicochemical and microbiological parameters.

PCA retained five principal components explaining 74.8% of the total variance and identified nine priority parameters controlling spatiotemporal variability: *E. coli*, total coliforms, water temperature, BOD_5, $N–NO_3^-$, $N–NH_4^+$, turbidity, Mn, and total dissolved Fe. Two-way ANOVA revealed significant seasonal differences, with higher rainy-season values of *E. coli*, $N-NO_3^-$, $N–NH_4^+$, turbidity, Fe, and water temperature. Spatially, water quality was generally better in the upstream reaches of the Huong and Bo rivers, whereas the Phu Bai River showed the most pronounced deterioration and recurrent pollution hotspots. For the 16 riverine monitoring sites, VN_WQI classified 42% of observations as excellent, 31% as good, 23% as average, and 4.2% as poor; both monitoring location and season had significant effects on VN_WQI values.

Overall, the results indicate that water-quality deterioration in the study area was hotspot-driven and seasonally amplified, rather than occurring uniformly across the system. The proposed framework provides a practical basis for resource-efficient adaptive monitoring and future water governance.

Keywords: Huong river; Tam Giang lagoon; surface water quality; principal component analysis; Thua Thien Hue; water quality index.

1. INTRODUCTION

Surface water quality is crucial to human and ecosystem health, directly influencing the sustainable development of regions.[1] However, increasing pressures from urban expansion, industrial activities, agricultural runoff, and domestic wastewater discharge have intensified the deterioration of surface water resources in many parts of the world.[2] In coastal and low-lying regions, such as Central Vietnam, these pressures are likely exacerbated by climate-related stressors such as sea level rise, increased storm frequency, flooding, and heavy precipitation patterns,[3] which might intensify pollution transport, particularly during the rainy season. Translating complex monitoring datasets into management-relevant evidence therefore requires approaches that can both summarize overall status and diagnose the parameters that drive variability.[4,5]

Normally, water quality can be assessed using two broad approaches: (i) assessment based on individual parameters, and (ii) water quality indices (WQIs). Assessing water quality on a parameter-by-parameter basis remains a fundamental approach because it preserves the original information of each measured variable and allows direct identification of exceedances and their likely environmental significance, whether related to organic pollution, nutrient enrichment, microbial contamination, or

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metal inputs. This approach is particularly valuable for compliance monitoring, since water-quality interpretation is inherently linked to the intended water use and the regulatory framework applied [6]. From a scientific perspective, however, its main limitation is that it treats aquatic systems as a set of isolated variables, whereas actual water quality results from simultaneous physical, chemical, and biological interactions. Consequently, single-parameter assessment often produces fragmented conclusions: it can identify which variables are problematic, but it is less effective in describing the overall impairment status of a water body or the covariance structure among variables across space and time, particularly when many variables are monitored simultaneously.[7,8] The second method is based on the use of a Water Quality Index (WQI), which integrates multiple parameters into a single value, making the results easier to interpret and communicate to managers, policymakers, and the general public [9,10]. Widely used examples include the National Sanitation Foundation Water Quality Index (NSF-WQI), [11,12] the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI). [11] At the national level, Vietnam has adopted the Vietnam Water Quality Index (VN_WQI) as a context-specific tool. [13] The NSF-WQI is a fixed-structure index based on a predefined set of nine core parameters and weighted aggregation, making it simple, communicable, and widely used for general river-water quality assessment. However, its fixed weighting system may be less adaptable to local regulatory priorities and hydro-environmental conditions. [10,14] In contrast, the CCME-WQI is a more flexible objective-based framework that does not require a fixed number of parameters; instead, it evaluates water quality according to the scope, frequency, and amplitude of exceedance relative to selected water-quality objectives. This flexibility allows CCME-WQI to be applied to multiple water-use purposes, including drinking, irrigation, and aquatic life protection, but also makes the results highly dependent on the choice of objectives and parameter sets. [9,15] VN_WQI differs from both indices in that it is a policy-oriented national framework specifically developed for Vietnamese inland surface waters, using a prescribed set of physicochemical and microbiological indicators that are directly linked to the domestic regulatory context. Despite their practical value, most WQI frameworks share important limitations: WQI values alone can obscure which pollutants

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(or groups of parameters) are most responsible for observed degradation, and the choice of parameters and weighting schemes remains a major source of variability and uncertainty across WQI models. [9]

Multivariate statistical techniques—especially principal component analysis (PCA)—have been widely used to explore complex water quality datasets. PCA reduces data dimensionality, identifies the most influential variables, and helps reveal the main natural and anthropogenic factors controlling spatial and temporal variations in water quality. Compared with expert-based weighting approaches (e.g. Delphi method [9,16]), PCA can provide a more objective basis for parameter prioritization and reduce redundancy among monitored variables. [17–19] Importantly, PCA can be deployed either (i) as an explicit step in developing a new WQI model [20,21] or (ii) as a complementary diagnostic tool alongside an existing policy index, to clarify which parameters dominate spatiotemporal variability.

Vietnam, a tropical country with a long coastline, serves as a typical example of a region severely affected by climate change,[22–24] witnessing a sharp increase in urbanization and industrialization.[25,26] These factors strongly affect environmental quality,[27] including water quality. In Central Vietnam, the Huong River–Tam Giang lagoon system is a particularly important setting for such an integrative assessment. Also, this water body system is underpinning the region's socioeconomic development.[28,29] In recent years, the water quality of both the river system and the Tam Giang lagoon has been increasingly compromised due to anthropogenic pressures, causing pollution and the progressive degradation of these critical water resources.[30,31] Several studies have been conducted, applying water quality assessment methods based on individual parameters.[32–34] Department of Natural Resources and Environment of Hue City also conducts annual monitoring programs on surface water quality for the entire system of canals, rivers, and lakes in the province.[35,36] In the meantime, the WQI index has been previously applied to this area.[37] Overall, these studies provide various perspectives on the water quality dynamics of the river-lagoon system in this region. However, due to the fragmented nature of the publications in terms of time and space, as well as the use of different methodologies, it is difficult to compare the results and construct a comprehensive picture of surface water pollution levels of the region. What remains insufficiently addressed is an

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assessment that simultaneously (a) communicates overall river water-quality status in a policy-consistent manner (*e.g.* VN_WQI) and (b) identifies, in a data-driven way, the key parameters that control seasonal variability and potential pollution hotspots, which are critical for designing efficient monitoring and targeted mitigation strategies. To address this gap, based on 20 sampling sites and 12 monitoring campaigns, this study evaluates water quality across a river–lagoon continuum, rather than limiting the analysis to a single river branch or treating river and lagoon waters as disconnected environments. We measured 18 physicochemical and microbiological parameters, applied PCA to describe multivariate structure, and also to prioritize monitoring variables, thus informed the selection of key indicators for future assessment programs. The findings extend beyond site-specific diagnosis by generating implications for adaptive monitoring and water governance, particularly in hydrologically complex transitional systems where management requires both ecological integration and temporal responsiveness.

II. METHODOLOGY

2.1. Study design, study area, and sampling strategy

This study was designed to address four methodological objectives: (i) to characterize the spatiotemporal variation of surface water quality across a hydrologically connected river–lagoon continuum, (ii) to evaluate individual parameters against applicable national standards, (iii) to identify the most influential parameters controlling water quality variability using principal component analysis (PCA), and (iv) to assess overall river-water quality using the Vietnam Water Quality Index (VN_WQI). In line with these objectives, a monitoring network covering both riverine and lagoon environments was established and repeatedly sampled over dry and rainy seasons.

The Huong River system, a fan-shaped catchment of 2,830 square kilometers, is composed of three primary tributaries: the Bo River, the Huu Trach River, and the Ta Trach River (the main stream). Based on its morphological characteristics, the main stream can be divided into two distinct segments. The mountainous segment is characterized by a steep riverbed with numerous rapids and is not influenced by tides. In contrast, the plain segment exhibits a gentler, meandering flow and is

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significantly impacted by tidal fluctuations and salinity levels.[38] Tam Giang – Cau Hai lagoon system extends in a northwest-southeast direction along the coastline, with a length of 68 km and a total water surface area of 216 km². It consists of three interconnected lagoons: Tam Giang Lagoon, Thuy Tu Lagoon, and Cau Hai Lagoon.[38] In this region, the typical weather characteristic includes the dry season, lasts from March to August, and the rainy season, lasts from September to February of the following year.

A total of 20 monitoring sites were selected to represent the river–lagoon continuum, including 13 riverine sites and 7 lagoon sites (**Figure 1; SI Table S1**). The monitoring period began in June 2022, when the finalized sampling design was implemented, and 12 consecutive campaigns were then conducted until December 2023 to ensure coverage of both the dry and rainy seasons, yielding 240 site-time observations. At each site, surface grab samples were collected in accordance with TCVN 6663-6:2018.[39] In situ measurements were performed immediately for water temperature (from now on stated as temperature), pH, dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), salinity, and turbidity using a calibrated Horiba U-52 multiparameter meter. Samples intended for laboratory analysis were transferred into clean containers appropriate for each analyte, preserved and stored according to TCVN 6663-3:2016,[40] transported to the laboratory under cooled and dark conditions, and analyzed within the holding times specified in the corresponding standard methods. The laboratory-determined parameters included total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), nitrate ($N–NO_3^-$), ammonium ($N–NH_4^+$), orthophosphate ($P–PO_4^{3-}$), total iron (Fe), manganese (Mn), total hardness, total coliforms, and *E. coli*. Quality assurance/quality control (QA/QC) included calibration verification, blank measurements, repeatability, recovery, limit of detection (LOD), and limit of quantification (LOQ), as summarized in **Table 1**.

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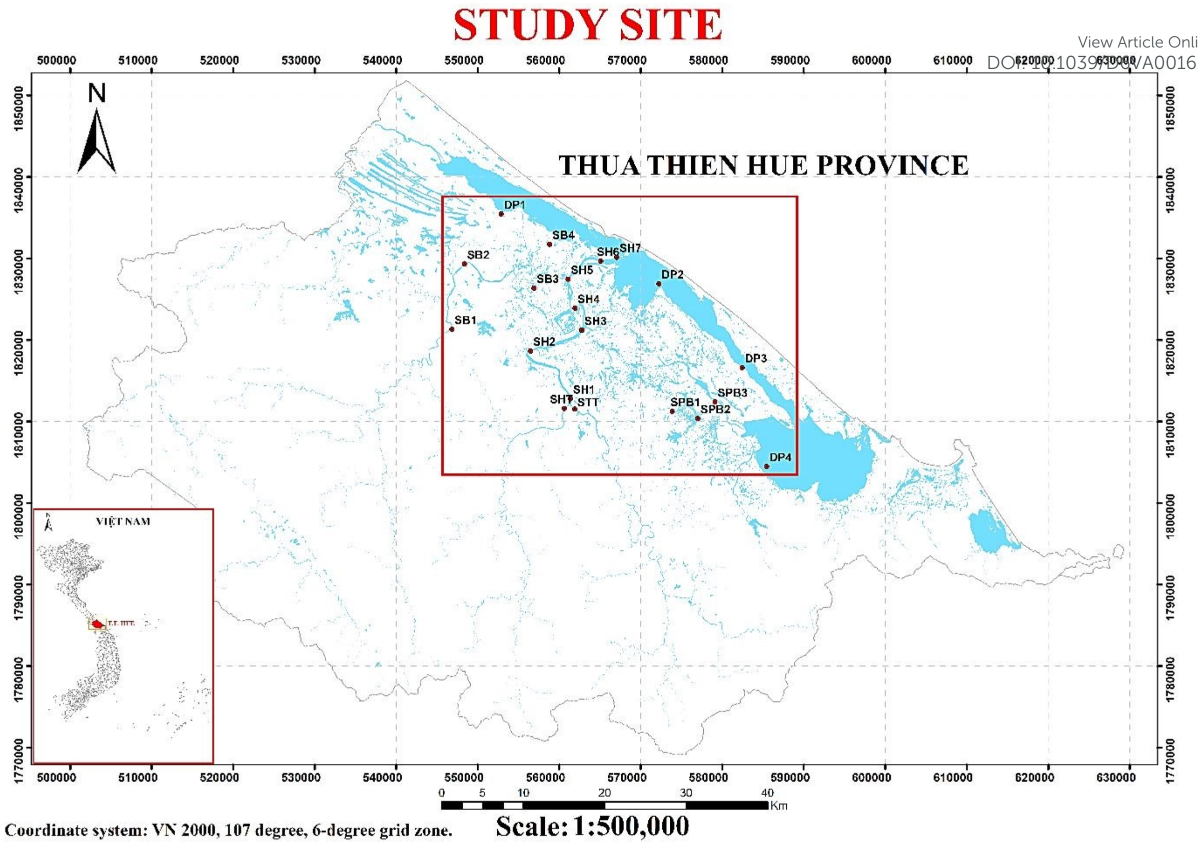

Figure 1. Location of the 20 surface-water sampling sites across the Huong River–Tam Giang lagoon continuum, Central Vietnam

Table 1. Analytical methods and QA/QC performance

No.	Parameters	Unit	LOD/range	LOQ	Recovery (%) (n = 3)	RSD (%) (n = 3)	Calibration curves	Method
1	Temperature	(°C)	**4 ÷ 50**		100%	0.1 %	None	field measurements/Horiba U52 equipment
2	pH	-	**2 ÷ 12**		100%	0.1 %	None	field measurements/Horiba U52 equipment
3	DO	mg/L	**0 ÷ 16**		100%	0.3 %	None	field measurements/Horiba U52 equipment
4	EC	µS/cm	**0 ÷ 50000**		99%	0.3 %	None	field measurements/Horiba U52 equipment
5	TDS	mg/L	**0 ÷ 50000**		104%	0.7 %	None	field measurements/Horiba U52 equipment
6	Salinity	‰	**0 ÷ 70**		100%	0.5 %	None	field measurements/Horiba U52 equipment
7	TUR	NTU	**0 ÷ 800**		100%	0.4 %	None	field measurements/Horiba U52 equipment
8	TSS	mg/L	**2**	**7**	102%	8 %	None	Gravimetric method by filtration through glass-fibre filters, TCVN 6625:2000
9	BOD_5	mg/L	**1.1**	**3.6**	93%	7 %	None	Dilution and seeding method with allylthiourea addition, TCVN 6001-1:2008
10	COD	mg/L	**3**	**9**	97%	6 %	None	Closed reflux, titrimetric method, SMEWW 5220-C:2017
11	$N\text{-}NO_3^-$	mg/L	**0.006**	**0.017**	98%	5 %	$y = 0.0236 + 4.0054x$ ($R^2 = 0.9990$)	Sulfosalicylic acid spectrometric method, TCVN 6180:1996

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12	N-NH_4^+	mg/L	**0.007**	**0.021**	97%	4%	y = 0.0294 + 1.0796x (R^2 = 0.9995)	Manual spectrometric salicylate–hypochlorite method, TCVN 6179-1:1996
13	P-PO_4^{3-}	mg/L	**0.006**	**0.018**	90%	4%	y = 0.0007 + 0.7314x (R^2 = 0.9996)	Ammonium molybdate spectrometric method, TCVN 6202:2008
14	Fe	mg/L	**0.03**	**0.1**	101%	3%	y = 0.0127 + 0.9927x (R^2 = 0.9997)	*1,10-phenanthroline spectrometric method* , TCVN 6177:1996
15	Mn	mg/L	**0.017**	**0.06**	94%	3%	y = 0.0023 + 0.1900x (R^2 = 0.9994)	Direct air–acetylene flame atomic absorption spectrometric method, SMEWW 3111B:2017
16	Total hardness	mg/L	**3.0**	**8.0**	94%	4%	None	*EDTA titrimetric method* (SMEWW 2340C:2017), SMEWW 2340C:2017
17	Total Coliforms	MPN/100mL	**3**	**3**	None	2%	None	Multiple-tube most probable number (MPN) method, TCVN 6187-2:1996
18	*E.coli*	MPN/100mL	**3**	**3**	None	1%	None	Multiple-tube most probable number (MPN) method, TCVN 6187-2:1996

LOD, limit of detection; LOQ, limit of quantification; RSD, relative standard deviation; MPN, most probable number.

2.2. Principal component analysis for parameter prioritization

To identify the parameters contributing most strongly to spatial and temporal water-quality variation, PCA was applied to the dataset of 18 physicochemical and microbiological variables. Prior to PCA, all variables were standardized using z-scores to eliminate differences in scale and measurement units. Components with eigenvalues ≥ 1.0 were retained according to the Kaiser criterion. The proportions of explained variance and cumulative explained variance were used to evaluate the contribution of retained components to the overall data structure. Variable importance was interpreted using the squared cosine ($\cos^2$) values and the cumulative contribution of each variable across retained principal components. Based on these contributions, a relative weight (w_i) was assigned to each variable, and parameters with the highest cumulative loadings were considered the most influential for water-quality assessment and prioritization of future monitoring. This use of PCA was therefore not limited to descriptive ordination, but was also intended to support the identification of key indicators for a more targeted and adaptive monitoring strategy.[33]

2.3. Water quality assessment based on WQI

To provide an integrated and policy-relevant assessment of river-water quality, the Vietnam Water Quality Index (VN_WQI) was calculated following the Technical Guidance for Calculation and Publication of Vietnam Water Quality Index issued together with Decision No. 1460/QD-TCMT

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dated 12 November 2019 [13]. VN_WQI was selected instead of the widely used NSF-WQI [11,12] or CCME-WQI, [11] as it is specifically designed for Vietnamese surface waters, incorporating local regulatory thresholds and pollution contexts, and thus provide more policy-relevant information for local water governance and decision-making. More generally, when applying WQI frameworks in other regions or countries, it is advisable to develop or adapt context-specific indices that align with the local hydro-climatic conditions, dominant pollution sources, and regulatory standards, ensuring both scientific robustness and policy relevance. [41,42]

Because the VN_WQI framework applies to inland surface water, only data from the 16 riverine sites were used in the index calculation. The parameters included in the VN_WQI calculation were: pH, DO, BOD_5, COD, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, Coliform, *E. coli*. Parameters such as heavy metals and pesticides were not included in the calculation of VN_WQI in this study because the observed values in the past 10 years were all < LODs, showing an insignificant contribution to background water quality. In other words, fluctuations of water quality in the study area were not determined by these factors. Detailed procedures for the VN_WQI calculation are provided in **Supporting information SI Text.**

2.4. Statistical analysis

For analytical results below the detection limit (LOD) values were assigned as the detection limit itself; results below the quantification limit (LOQ) were assigned the LOQ to avoid bias in statistical analyses. [43] The proportion of censored data varied by parameter: BOD_5 had ~44% values below LOD, Mn had 34%, P-PO4 had 24%, while other parameters had < 10% censored data.

Microsoft Excel 2023 was used for data storage and WQI calculation, while Sigma Plot 14.0 was employed to process experimental data, including descriptive statistics, statistical testing, and principal component analysis (PCA), and bootstrap analysis was performed in Python using a nonparametric resampling procedure (10,000 iterations, with replacement). The Shapiro–Wilk test ($p = 0.05$) was used to assess the normality of the data. If the data met the normality assumption, differences among groups were tested using one-way ANOVA followed by Tukey's post hoc test. In

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cases where the data did not meet normality assumptions, non-parametric methods were applied, specifically the Kruskal–Wallis H test, to evaluate group differences. Dunn's test was then applied to identify specific group differences between the groups. To quantify uncertainty, 95% confidence intervals were reported for means or medians as appropriate, and statistical significance was set at $p<0.05$. Bootstrap estimates of the mean and 95% percentile confidence intervals were calculated for dry- and rainy-season VN_WQI values at each site and for the pooled dataset.

3. RESULTS AND DISCUSSION

3.1. Surface Water Quality Assessment

3.1.1. Variations in water quality of the Huong river, tributaries, and lagoon areas

A summary of water quality parameter variations in the Huong River, its tributaries, and the lagoon area from June 2022 to December 2023 is presented **in Table 2**, with the following key findings:

For the Huong River and its tributaries:

- Parameters such as water temperature, pH, EC, TDS, $P\text{-}PO_4^{3-}$, and hardness met domestic water quality standards (QCVN 08:2015[44] and QCVN 08:2023[45]). Most measurements for $N\text{-}NO_3^-$ and BOD_5 also complied, except at several locations during rainy months. Some parameters, including salinity, total coliforms, and *E. coli*, consistently exceeded standards across most sampling sites, especially in the rainy season—indicating widespread salinization and microbial contamination possibly from untreated domestic wastewater or agricultural runoff during heavy rains. Total dissolved iron (Fe) also exceeded standards at multiple sites, consistent with previous studies.[33,46] Currently, *Quan et al.* showed projections of increased rainy season flows, rising of water temperature by 0.2 to 3.5 °C and annual rainfall by 1 to 8% for the Huong Basin, facilitating pollution transport under climate change scenarios.[47]

- Parameters showing high variability (CV > 100%) included salinity (634.4%), TDS (552.4%), EC (551.9%), hardness (273.6%), $N\text{-}NO_3^-$ (218.6%), *E. coli* (215.5%), total coliforms (177.9%), $N\text{-}NH_4^+$ (174.7%), TSS (160.6%), and turbidity (149.3%). These fluctuations may result from sampling across

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diverse locations, from freshwater upstream (STT, SHT, lower values) to brackish estuarine regions (SH7, higher values),[46] exacerbated by tidal influences and less rainfall events in dry season. This pattern is consistent with broader concerns in coastal Vietnam and other Southeast Asian coastal regions, where saltwater intrusion and sea-level rise are increasingly affecting riverine and estuarine water quality.[48]

For the Tam Giang Lagoon system:

This area, classified as coastal marine waters per QCVN 10:2023/BTNMT,[49] was assessed using corresponding marine water standards.

Among 18 monitored parameters, most met the criteria under TCVN 13951:2024. However, salinity, N-NH_4, COD, total dissolved Fe, total coliforms, and *E. coli* exceeded limits. Particularly concerning is microbial pollution (coliforms and *E. coli*), which poses a risk of waterborne diseases and impacts fishery productivity.

Parameters with strong variation included *E. coli* (213.3%), N-NO_3^- (126.9%), N-NH_4^+ (123.7%), and P-PO_4^{3-} (112.7%), though overall variability in the lagoon was lower than that of the rivers. The lower overall CV in the lagoon compared to the rivers suggests a buffering effect from tidal mixing and larger water volume, which dilutes pollutants but does not eliminate chronic issues like microbial contamination (*e.g. E. coli* max = 1100 MPN/100 mL, 45% exceeding standards). High CV for nutrients (N-NO_3^-, N-NH_4^+, P-PO_4^{3-} > 100%) indicates pulsed inputs from river discharges, particularly during the rainy season. In the meantime, although BOD_5 values generally complied with the regulatory thresholds, COD exceeded permissible limits in 96% of lagoon samples. This discrepancy suggests that a large fraction of the organic matter in the lagoon is refractory and not readily biodegradable, likely originating from aquaculture residues and natural humic substances. Such conditions indicate a chronic organic load that may not pose immediate oxygen depletion risks, but can impair water quality in the long term.

Table 2. Summary statistics of 18 water-quality parameters in riverine and lagoon sites during 12 monitoring campaigns (June 2022–December 2023)

	Huong river and tributaries							Lagoon						
Parameters	QCVN 08 (surface)*	n	Max	Min	Median	CV (%)***	% > QCVN	QCVN 10 (coastal marine)/ TCVN 13951**	n	Max	Min	Median	CV (%)***	% > QCVN or TCVN
Temperature (^{o}C)	-	191	37.5	22	27.1	12.0	0	18-33	48	34.8	21.1	28.15	12.5	8
pH	6-8.5	191	8	6.1	6.9	5.5	0	6.5-8.5	48	8.5	6.7	7.5	5.5	0
DO (mg/L)	6	191	8	4.4	6.2	10.3	38	5	48	7	5	6.2	8.3	0
EC (µS/cm)	-	191	24400	26	49	551.9	0	-	48	36900	94	8145	85.7	0
TDS (mg/L)	-	191	15900	14.95	32	552.4	0	-	48	23900	61	5305	85.7	0
Salinity (‰)	-	191	14.7	0	0	634.4	-	20-36	48	23.2	0	4.6	90.1	0
TUR (NTU)	-	191	800	0	31.2	149.3	14	-	48	131	0	27.9	90.9	0
TSS (mg/L)	25	191	211	< LOD	7.3	160.6	17	50	48	36	< LOD	7	65.6	0
BOD_5 (mg/L)	4	191	20.1	< LOD	3.6	83.8	4	-	48	5.3	< LOD	3.6	46.3	0
COD (mg/L)	10	191	49.3	< LOD	9	56.0	38	4	48	29.7	< LOD	9.8	45.5	96
$N\text{-}NO_3^-$ (mg/L)	2	191	2.65	< LOD	0.06	218.6	1	-	48	0.346	< LOD	0.02	126.9	0
$N\text{-}NH_4^+$ (mg/L)	0.3	191	1.443	< LOD	0.05	174.7	4	0.1	48	0.911	< LOD	0.07	123.7	44

P-PO_4^{3-} (mg/L)	0.1	191	0.074	< LOD	0.02	72.6	0	0.2	48	0.234	< LOD	0.02	112.7	2
Fe (mg/L)	0.5	191	2.72	< LOD	0.39	89.7	40	0.5	48	1.72	0.1	0.23	98.1	21
Mn (mg/L)	0.1	191	0.42	< LOD	0.06	82.1	21	0.5	48	0.16	< LOD	0.04	73.5	0
Total coliforms (MPN/100mL)	1000	191	24000	23	1100	177.9	63	1000	48	2100	43	460	86.0	33
Total hardness (mg/L)	-	175	704	7.6	14	273.6	0	-	44	4160	15	881.5	95.0	0
E. coli (MPN/100mL)	20	176	4600	< LOD	93	215.5	89	50	44	1100	< LOD	43	213.3	45

QCVN 08 (surface): QCVN 08:2023/BTNMT or QCVN 08:2015/BTNMT. National technical regulation on surface water quality

***QCVN 10 (coastal marine): QCVN 10:2023/BTNMT. National technical regulation on marine water quality.*

****CV: Coefficient of Variation*

% > QCVN or TCVN: Percentage of samples exceeding the applicable standard (%)

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3.1.2. Identification of priority water-quality parameters

The degree of influence - or importance - of specific water quality parameters on overall water quality has traditionally been determined using expert opinion surveys, notably the Delphi method developed by the RAND Corporation.[50] McClelland is considered the pioneer of this approach,[51] initially selecting nine parameters (Fecal coliform, pH, BOD_5, total NO_2^- and NO_3^-, total phosphorus, temperature, turbidity, TSS, and DO), which were later integrated into the U.S. Water Quality Index (WQI) model.[12] In other studies, key parameters such as ammonium, Ca, Cl, chlorophyll-a, electrical conductivity (EC), fluoride (F), hardness ($CaCO_3$), Mg, Mn, N-NO_3, pH, SO_4^{2-}, and turbidity were selected based on their impact on ecosystems and human health. with assigned weights reflecting their influence on overall water quality assessment.[52] Besides the Delphi method, multivariate statistical analyses, such as Principal Component Analysis (PCA), have been widely applied to identify key water quality parameters objectively.[18,53–55]

In this study, principal component analysis (PCA) was used to identify the dominant drivers of spatiotemporal variability in water quality across the river–lagoon continuum based on 18 monitored parameters. **Table 3** presents the eigenvalues, proportions of variance, and cumulative variances of principal components derived from the PCA.

Table 3. Eigenvalues, proportions of variance, and cumulative variances of 18 principal components (PCs)

PC	Eigenvalues	Proportions of variance (%)	Cumulative variances (%)
1	4.929	27.382	27.382
2	3.405	18.918	46.3
3	2.293	12.74	59.04
4	1.45	8.057	67.097
5	1.384	7.69	74.788
6	0.969	5.386	80.173
7	0.761	4.227	84.4
8	0.693	3.852	88.252

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9	0.483	2.686	90.938
10	0.431	2.397	93.335
11	0.345	1.917	95.251
12	0.318	1.766	97.018
13	0.23	1.276	98.293
14	0.173	0.959	99.252
15	0.103	0.575	99.827
16	0.0305	0.17	99.996
17	0.000685	0.00381	100
18	0.00000109	0.00000608	100

The first five principal components (PC1–PC5) had eigenvalues greater than 1 and together explained approximately 74.8% of the total variance, indicating that they captured most of the meaningful structure in the dataset. The remaining components (PC6–PC18) are considered background variation or "noise" within the dataset.

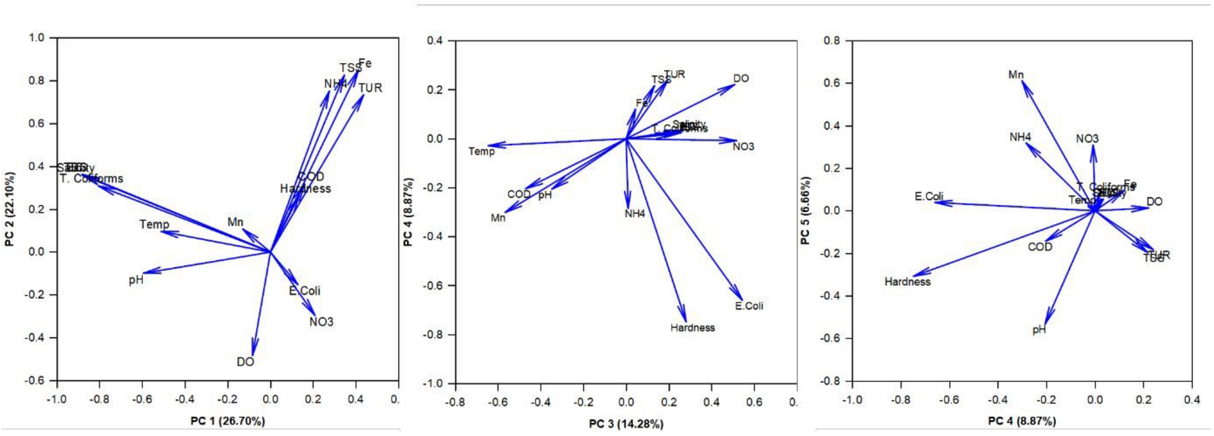

Figure 2. PC loadings of the 18 investigated parameters

Figure 2 provides additional insight into the covariance structure of the monitored variables. In the loading plots, turbidity, TSS, Fe, and N–NH_4^+ tend to cluster in similar directions, suggesting that these variables are co-regulated and likely associated with runoff-driven transport of suspended matter and particle-bound pollutants. By contrast, *E. coli* and total coliforms do not fully overlap, indicating that the two microbial indicators may reflect partly different source pathways or hydrological controls across the river–lagoon continuum. Dissolved oxygen (DO) is oriented broadly opposite to the organic–nutrient–microbial

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variables, which is consistent with oxygen depletion under deteriorated water-quality conditions. The higher-order axes further separate secondary gradients, including those related to Mn, total hardness, and ionic variables, but these patterns should be interpreted cautiously because PC4 and PC5 account for a substantially smaller share of the total variance than PC1–PC3. Overall, the loading structure supports the interpretation that water-quality variability in the study area is governed primarily by microbial contamination, runoff-associated nutrient and sediment transport, and localized metal enrichment.

The cos² values and the total contribution of each variable to the five retained components (PC1–PC5) were then calculated and are presented in **Table 4**.

Table 4. Weights of the 18 water quality parameters (*)

		PC 1	PC 2	PC 3	PC 4	PC 5	**Total PC**	**Weight**	**Order**
1	**Temperature**	**0.178**	**0.0904**	**0.113**	**0.457**	**0.353**	**1.1914**	**0.96**	**3**
2	pH	0.247	0.107	0.13	0.315	0.00361	0.80261	0.64	17
3	DO	0.0648	0.153	0.0558	0.0279	0.509	0.8105	0.65	16
4	EC	0.388	0.246	0.0957	0.0631	0.039	0.8318	0.67	13
5	TDS	0.388	0.246	0.0956	0.0631	0.039	0.8317	0.67	14
6	Salinity	0.388	0.246	0.0981	0.0611	0.0391	0.8323	0.67	15
7	**Turbidity**	**0.259**	**0.307**	**0.262**	**0.121**	**0.0207**	**0.9697**	**0.78**	**8**
8	TSS	0.241	0.35	0.225	0.032	0.00917	0.85717	0.69	11
9	**BOD$_5$**	**0.0467**	**0.23**	**0.463**	**0.18**	**0.188**	**1.1077**	**0.89**	**4**
10	**COD**	**0.142**	**0.309**	**0.314**	**0.0997**	**0.0477**	**0.9124**	**0.73**	**10**
11	**N-NO$_3^-$**	**0.0932**	**0.115**	**0.451**	**0.0461**	**0.355**	**1.0603**	**0.85**	**5**
12	**N-NH$_4^+$**	**0.0649**	**0.232**	**0.391**	**0.223**	**0.107**	**1.0179**	**0.82**	**7**
13	P-PO$_4^{3-}$	0.00675	0.301	0.0522	0.393	0.0404	0.79335	0.64	18
14	**Fe**	**0.257**	**0.25**	**0.115**	**0.258**	**0.17**	**1.05**	**0.84**	**6**
15	**Mn**	**0.0467**	**0.0462**	**0.134**	**0.121**	**0.596**	**0.9439**	**0.76**	**9**
16	**Total Coliforms**	**0.211**	**0.278**	**0.229**	**0.393**	**0.12**	**1.231**	**0.99**	**2**
17	Total hardness	0.383	0.242	0.0997	0.0759	0.0404	0.841	0.68	12
18	***E. Coli***	**0.18**	**0.227**	**0.233**	**0.418**	**0.187**	**1.245**	**1.00**	**1**

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PCA results revealed parameters played significant role in influencing surface water quality variability, ranked by their total contribution (weight, > 0.7): *E. coli (1.00), total coliforms (0.99), temperature (0.96),* BOD_5 *(0.89),* $N\text{-}NO_3$ *(0.85), Fe (0.84),* $N\text{-}NH_4$ *(0.82), turbidity (0.78), Mn (0.76), and COD (0.73).*

The high influence of E. coli and total coliforms (weights 1.00 and 0.99) underscores the critical role of microbial pollution in the Huong River–Tam Giang system, but originated from different sources. While microbial pollution in the rivers were likely driven by untreated domestic sewage and agricultural runoff, the main source of bacterial pollution in the lagoon area were from aquacultural productions (occupying an area of 70 km^2 out of a total of 216 km^2 of surface water in the lagoon). Many studies on tropical surface waters have demonstrated that microbial contamination (e.g.. *E. coli*. coliforms) is strongly influenced by land use practices, wastewater discharges, and livestock activities. [56–59] In tropical environments, particularly in Central Vietnam, high rainfall and hydrological dynamics further enhance the mobilization and persistence of these microbial indicators, highlighting the importance of considering both point and diffuse sources.

BOD_5 (weight 0.89) and COD (0.73) were also identified as the primary drivers shaping surface water quality in this study, signifying the strong influence of organic pollution in this region. Similar relationships between elevated BOD/COD and degraded surface-water quality have been reported regionally and globally — for example, in freshwater systems of the Vietnamese Mekong Delta [60,61], and in river basins of China [62] and the Pantanal region [63] where COD and BOD (and their effects on DO) consistently ranked among the top factors controlling water quality.

Nutrient parameters ($N\text{-}NO_3^-$: 0.85. $N\text{-}NH_4^+$: 0.82) highlight agricultural inputs, particularly during the rainy season. Temperature (0.96) influences microbial growth and

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oxygen solubility, turbidity (0.78) is linked to sediment mobilization during floods, reducing light penetration and impacting primary productivity. As for Mn and total dissolved Fe, although this parameter is rarely mentioned in related studies, it was found to be highly influential in surface water quality in Thua Thien Hue Province, especially in the Phu Bai River area. This is mainly due to wastewater discharge from industrial activities. Therefore, this study includes Mn and total dissolved Fe as an important parameter for subsequent assessments.

When compared with previous studies identifying key water quality parameters using the Delphi method, as discussed above, the PCA results overlapped with the following 8 parameters: microbial indicators (*E. coli*. total coliforms), temperature, $N\text{-}NO_3^-$, BOD_5, $N\text{-}NH_4^+$, turbidity, and total Mn. Given that total dissolved Fe also played spatio - seasonal a crucial role to the water quality assessment in this study area, the following nine key water quality parameters selected for further analysis are: *E. coli*, total coliforms, temperature, $N\text{-}NO_3^-$, BOD_5, $N\text{-}NH_4^+$, turbidity, Mn, and total dissolved Fe.

3.1.3. Spatial and seasonal variation of water quality

The general spatial **-** seasonal variations in surface water quality at 20 monitoring sites in dry season and rainy season, based on the nine key parameters selected above, are illustrated in the **Figure 3**.

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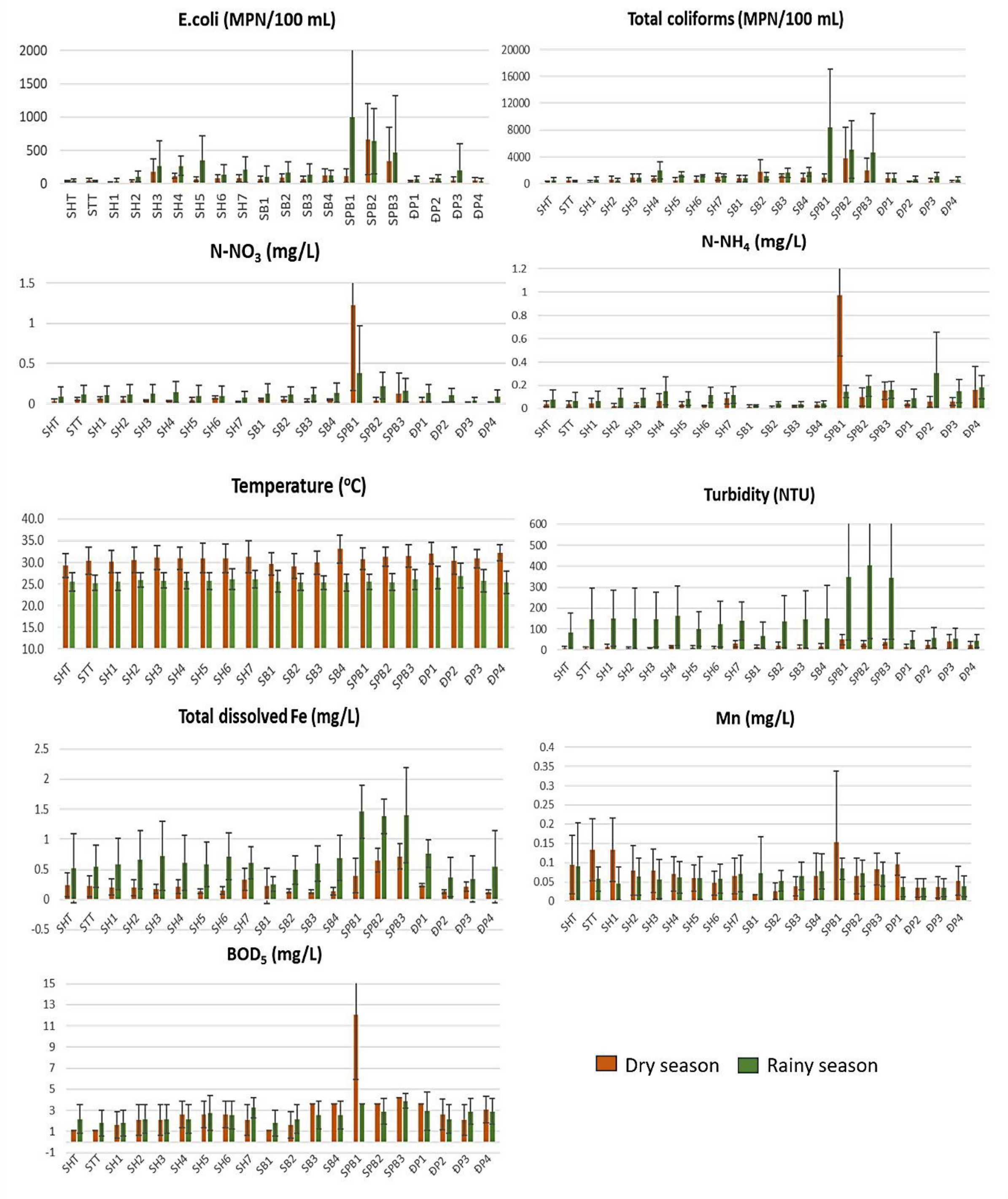

Figure 3. Spatial and temporal variation of nine key water quality parameters in the study region

Spatial variation:

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To preliminarily identify which areas were more polluted compared to others, we compared the mean (or median) values of water quality parameters across study locations. The results are presented in **Table 5**, where statistically significant differences ($p < 0.05$) between sites (rows) for a given parameter (column) are denoted by **"x"** for *statistically lower values* and **"X"** for *statistically higher values*. Parameters such as temperature, turbidity, and total manganese are not included in **Table 5** because there were no statistically significant differences in their average (or median) values among the surveyed sites in the study area.

In general, the spatial variation in water quality parameters between upstream and downstream sections, between the main river and its tributaries were minimal. In other words, geographical location did not have much impact on water quality fluctuations. However, the three sites SPB1, SPB2, and SPB3—located along the Phu Bai River—show statistically significant higher values (marked as "X") for multiple parameters, including *E. coli*, total coliforms, $N\text{-}NO_3^-$, BOD_5, $N\text{-}NH_4^+$, and total dissolved Fe. This indicates a serious level of pollution in this area, likely resulting from direct wastewater discharges from the Phu Bai Industrial Zone and unfavorable hydrological conditions, such as the riverbed relatively flat, with low slope, narrow width, and shallow water depth, that limit the river's self-purification capacity. In contrast, other locations showed no significant differences when compared to other sites. These findings provide a crucial basis for prioritizing areas for surface water quality monitoring and management in the study region.

Table 5. Statistical comparison ($p < 0.05$) of spatial differences in six key water quality parameters across 20 monitoring sites

No.	**Location**	***E. coli***				**TC**											**$N\text{-}NO_3$**		**BOD_5**						**$N\text{-}NH_4$**											**Total iron**					
1	STT	x					X								x				x				x		x																
2	SHT		X			x								x						X						x															
3	SH1			x				x								x											x														
4	SH2								x																			x													
5	SH3																																								

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6	SH4																																								
7	SH5																																								
8	SH6																																								
9	SH7																																								
10	SB1												x									x		x					x				x			x					
11	SB2																													x				x			x				
12	SB3																														x				x						
13	SB4																															x									
14	SPB1													X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X									X
15	SPB2	X	X	X	X	X	X	X	X	X	X	X	X																				X	X	X	X	X	X	X	X	
16	SPB3																						X	X																	
17	ĐP1																																								
18	ĐP2									x																												x			
19	ĐP3										x						x																						x		x
20	ĐP4				x							x						x																						x	

"x" indicates a statistically lower value at the specific site compared to the site marked with "X". p-value < 0.05. Temperature, turbidity, and total manganese are not included because there were no statistically significant differences.

Seasonal variation:

Figure 4 illustrates the seasonal variation (dry season vs. rainy season) of nine key water quality parameters selected through PCA. The results show statistically significant differences ($p < 0.05$) between the two seasons for 6 out of 9 parameters: *E. coli*, N-NO$_3^-$. N-NH$_4^+$, turbidity, total iron (Fe), and temperature. Among these, parameters such as N-NO$_3^-$. turbidity, and total iron exhibit notably higher values during the rainy season, reflecting the influence of surface runoff and the mobilization of pollutants from agricultural, domestic, and industrial sources. Heavy rainfall increases turbidity and contributes to the spread of pollution through runoff from agricultural areas (leading to nutrient pollution by N-NO$_3^-$ and N-NH$_4^+$). livestock farming zones along the riverbanks (*E. coli* contamination), and road construction activities in upstream areas (iron pollution). These factors collectively degrade the water quality of the Huong River, its tributaries, and the coastal lagoon system in Thua Thien Hue Province.

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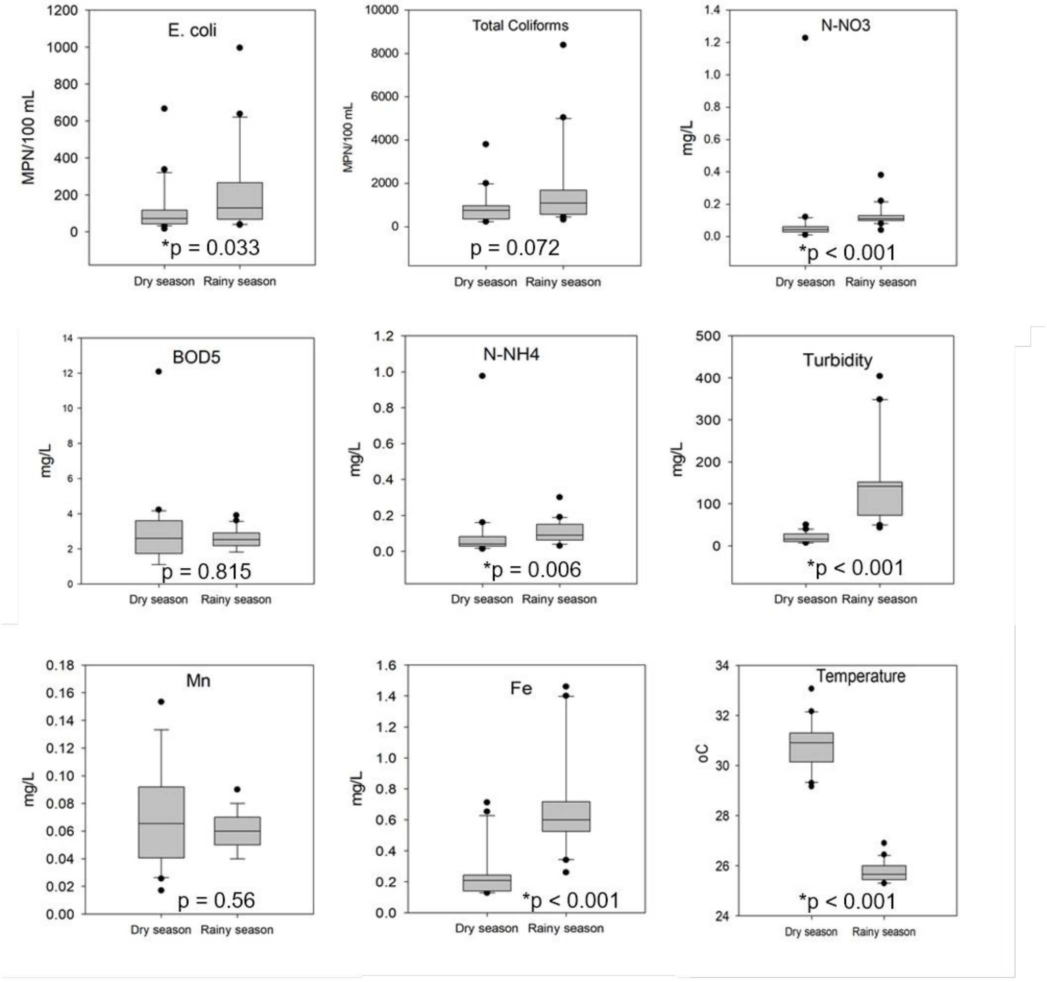

Figure 4. Seasonal variation of the nine PCA-prioritized water-quality parameters across the 20 monitoring sites. *Asterisks indicate statistically significant differences between the dry and rainy seasons (p<0.05).*

3.2. Water quality assessment based on VN_WQI

VN_WQI was used in this study to provide an integrated and policy-relevant summary of river-water quality at the 16 inland monitoring sites. During the monitoring period, 42% of VN_WQI values fell in the "Excellent" category, 31% in "Good", 23% in "Average", and 4.2% in "Poor", with no observations classified as "Very poor" (**Table 6**). Under the official Vietnamese guidance, WQI values of 91–100 indicate water that is generally suitable for

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domestic water supply, values of 76–90 indicate water that may be used for domestic supply with appropriate treatment, and values of 51–75 are more consistent with irrigation and similar purposes [13]. The "Good" and "Excellent" classes observed in this study primarily indicate favorable raw-water status for abstraction and treatment, not direct potability, as according to the WHO drinking-water perspective, *E. coli* should not be detectable in a 100 mL sample of drinking water, [64] but WQI alone has obscured the contribution of *E. coli* to this index.

Seasonal medians were calculated from the site-specific VN_WQI values reported in **Table 6** and demonstrated in **Figure 5.**

The two-way ANOVA results revealed statistically significant differences in WQI values between monitoring locations ($F = 9.341$, $p < 0.001$) and between seasons ($F = 8.347$, $p < 0.001$). The results of the Tukey post-hoc test reveal statistically significant differences in the mean VN_WQI values among several monitoring sites and months. During the dry season months of the survey period (June and August 2022, and April, June, August 2023), up to 87% of the VN_WQI values in this season fell within the "Good" to "Excellent" range. October and November 2023 consistently showed significantly lower mean VN_WQI values ($p < 0.05$) compared to earlier months. This suggests a marked deterioration in water quality toward the end of the rainy season, when flood events happened gradually, facilitating the transport of pollutants. In terms of spatial variation, monitoring sites located in the upstream areas of the Huong River (SHT, STT, SH1, SH2) mostly showed "Excellent" water quality throughout the year, significantly higher mean VN_WQI values compared to SPB1, SPB2, and SPB3 (sites located on the Phu Bai River), with p-values < 0.001. These patterns reinforce the conclusions drawn from the parameter-by-parameter assessment and PCA: water quality in the study area is not uniformly degraded, but rather exhibits hotspot-driven and seasonally amplified deterioration associated with hydrological events and localized anthropogenic pressures. These

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findings are align with the works of Hop et al, who used a different WQI model to evaluate the Huong River's water quality during the 2017–2020 period.[33] The interpretive value of VN_WQI in this study is supported by its consistency with both parameter-level exceedances and field-observed hotspot conditions. Sites with the lowest VN_WQI values, particularly SPB1–SPB3 along the Phu Bai River, also showed significantly elevated microbial, nutrient, BOD5_55, and dissolved Fe levels relative to most other locations, indicating that low WQI scores corresponded to independently observed water-quality deterioration rather than to index behavior alone. Likewise, the lower VN_WQI values recorded during late rainy-season months were consistent with the seasonal increase in runoff-sensitive parameters identified by the individual-parameter analysis and PCA.

WQI's strength lies in its integrative, communicable score, simplifying water quality for stakeholders. However, it obscures specific pollutant contributions, hindering source identification. For instance, at Phu Bai River sites (SPB1, SPB2, SPB3), VN_WQI values as low as 29–31 in October–November 2023 indicate severe degradation, but the index alone cannot pinpoint whether this is driven by high microbial loads, elevated metals, or nutrients. This limitation is critical in the Huong River–Tam Giang system, where diverse pollution sources—industrial discharges, urban wastewater, and agricultural runoff—require targeted interventions.

Bootstrap analysis (see **SI Table S2** for details) confirmed the robustness of the seasonal VN_WQI pattern. At the pooled level, the rainy season showed a lower mean VN_WQI than the dry season, with a bootstrap-estimated difference of -7.5 points (95% CI: -11.44 to -3.58), indicating a clear overall deterioration in river-water quality during the rainy season. At the site level, the lowest rainy-season mean VN_WQI values were consistently observed at SPB1, SPB2, and SPB3, whereas the highest dry-season means occurred at upstream/main-river sites

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such as SH1, SH2, SHT, and STT. In addition, bootstrap confidence intervals excluding zero for the rainy-minus-dry difference at SH1, SH2, SH4, and SH5 indicate statistically robust seasonal declines at these locations. These results also provide an estimate of uncertainty in seasonal VN_WQI patterns, showing that the overall rainy-season decline remained stable at the pooled level, whereas wider confidence intervals at the Phu Bai River sites reflected greater temporal variability and uncertainty at these pollution hotspots.

Recent studies elsewhere indicate that IoT- and ML-based systems can improve the timeliness of water-quality surveillance, [65,66] whereas remote sensing coupled with machine learning is especially promising for spatial tracking of optically active parameters such as turbidity and suspended matter. [67] These tools serve as near-real-time or forecasting/screening dashboard. From an application perspective, the present framework of this study also provides a practical foundation for future real-time monitoring. Because PCA reduced the original dataset to a smaller set of priority parameters, the results can support the design of a more resource-efficient monitoring system in which continuous or high-frequency observations focus on the variables that most strongly control water-quality variability rather than applying uniform effort across the entire network. Continuous sensing of water temperature, turbidity, conductivity/salinity, dissolved oxygen, and hydrometeorological variables could be combined with periodic laboratory measurements of microbial indicators, nutrients, and dissolved metals to build predictive models for VN_WQI classes or early-warning screening of deteriorating conditions.

Table 6. VN_WQI values at monitoring sites on the Huong River and other rivers in Hue city during the survey period (June 2022 to December 2023)

Location	Dry season					Rainy season						
	Jun-22	Aug-22	Apr-23	Jun-23	Aug-23	Oct-22	Nov-22	Dec-22	Feb-23	Oct-23	Nov-23	Dec-23
SHT	97	95	93	99	93	88	98	98	99	95	92	87
STT	100	99	97	87	93	99	88	98	95	91	94	94
SH1	100	100	98	99	98	100	94	94	99	94	86	86
SH2	100	90	98	99	99	97	98	83	95	70	86	82
SH3	99	87	72	90	86	96	98	74	74	71	83	86
SH4	98	83	81	90	87	85	73	73	74	69	74	73
SH5	99	88	85	100	90	92	73	73	74	78	85	82
SH6	97	88	81	95	100	95	93	73	83	85	93	87
SH7	100	98	79	88	95	94	97	73	74	71	95	73
SB1	99	98	87	87	87	99	98	98	97	72	89	88
SB2	96	97	86	75	87	97	98	73	72	74	90	87
SB3	-	98	86	86	86	97	73	93	97	73	93	87
SB4	99	97	81	73	90	89	84	73	85	73	94	89
SPB1	90	79	73	73	66	92	72	86	65	30	31	30
SPB2	97	95	72	73	30	92	72	71	64	30	31	64
SPB3	90	98	81	87	65	93	73	72	30	29	92	84

Excellent 91-100	Good 76-90	Fair 51-75	Bad 26-50	Very bad ≤ 25

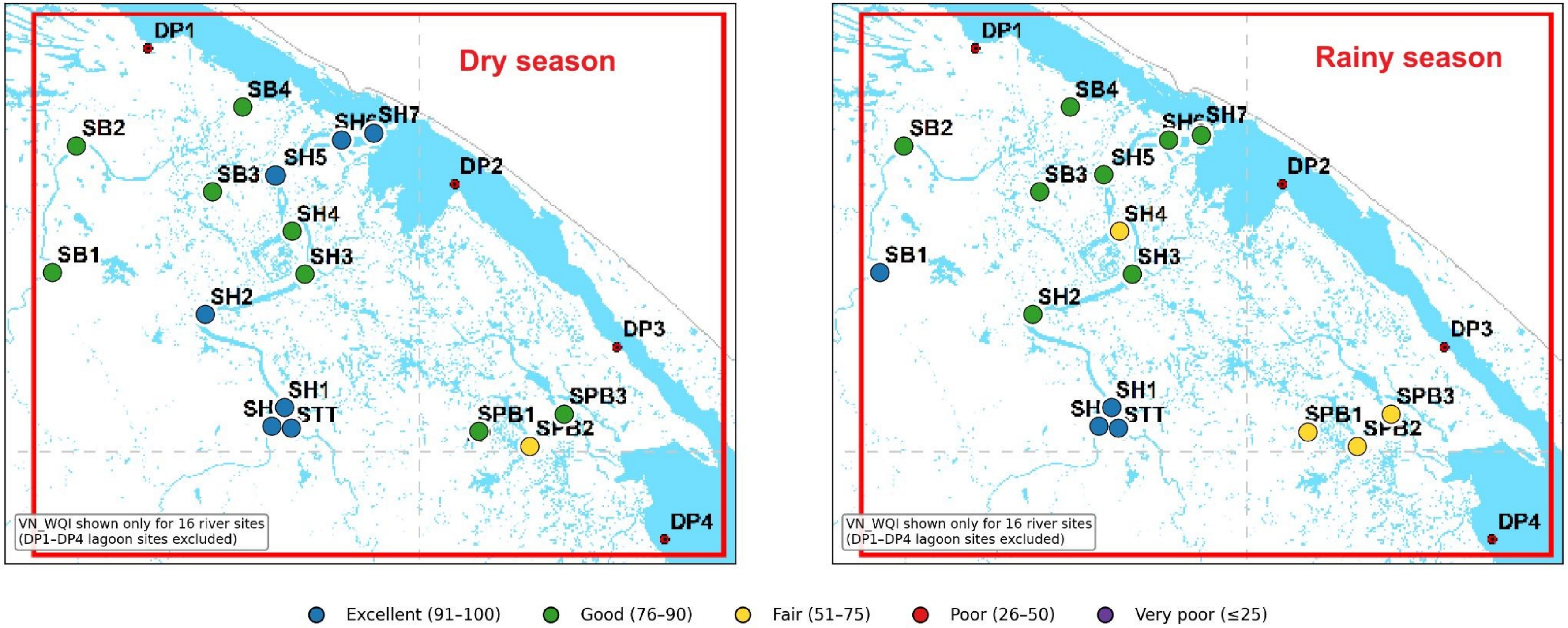

Figure 5. Spatial distribution of seasonal VN_WQI classes in the Huong River system

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CONCLUSIONS

This study presents an integrated framework for assessing surface-water quality across a river–lagoon continuum in Central Vietnam, helps fill the previously identified gap between policy-oriented water-quality classification and data-driven diagnosis of the parameters driving seasonal variability and pollution hotspots. PCA was first used to identify the parameters that exert the strongest influence on water quality, followed by an analysis of the spatial and temporal variation of individual parameters, while VN_WQI was applied to classify and communicate overall river-water quality. A key scientific contribution of the study is the demonstration that water-quality variability in this hydrologically connected system is not controlled equally by all monitored variables. Instead, PCA identified a smaller set of priority parameters - *E. coli*, total coliforms, temperature, BOD_5, $N–NO_3^-$, $N–NH_4^+$, turbidity, Mn, and total dissolved Fe - that captured most of the meaningful spatiotemporal structure in the dataset. The results also revealed a clear upstream–downstream and tributary-related gradient, with generally better water quality in the upstream reaches of the Huong and Bo rivers and more pronounced deterioration in the Phu Bai River and other human-impacted sites. Several parameters increased significantly during the rainy season, indicating that runoff and hydrological events such as heavy rainfall and flooding are major controls on water-quality deterioration in the study area.

From a management perspective, most river observations fell within the “good” to “excellent” VN_WQI categories, indicating relatively favorable raw-water conditions, particularly at upstream sites. However, these classifications should not be interpreted as evidence of direct potability, since microbiological contamination remained significant at many locations. This highlights the value of combining WQI with parameter-level analysis and PCA: WQI provides a clear overview for managers and the public, while individual parameters and

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PCA provide the diagnostic detail needed to identify pollution hotspots and likely drivers. These findings support an adaptive monitoring strategy in which upstream sites with consistently good water quality may be monitored less intensively, whereas tributaries and downstream hotspots, especially during the rainy season, should receive higher-priority surveillance and targeted mitigation. Beyond its scientific contribution, the study provides practical benefits for society by helping local authorities identify pollution hotspots, prioritize monitoring resources, and better protect water resources that support domestic supply, irrigation, fisheries, and local livelihoods. More broadly, the proposed framework can support adaptive water governance and contribute to sustainable water management in line with SDG 6 in vulnerable river–lagoon communities.

This study also has several limitations. VN_WQI was applicable only to inland river sites and therefore did not provide an equivalent integrated assessment for lagoon waters. In addition, although the monitoring dataset was seasonally repeated and sufficiently dense to detect spatiotemporal patterns, it may not fully capture short-term pollution pulses associated with extreme rainfall and flooding. Finally, while the study identified the main factors controlling water quality, it did not directly verify the dominant pollution sources.

Overall, the study shows that water governance in tropical river–lagoon systems can be strengthened through an assessment framework that combines communicable indices, parameter-level diagnosis, and data-driven prioritization of monitoring variables.

CRediT author statement

Nguyen Dinh Phuoc: Resources, Data curation, Methodology, Writing- Original draft. **Le Trung Hieu**: Investigation, Data curation, Visualization, Formal analysis, Writing - review & Editing. **Hoang Thai Long**: Conceptualization, Validation, Methodology, Supervision, Writing - review & editing. **Nguyen Van Hop**: Validation, Writing - review & editing. **Ho Xuan Anh Vu**: Investigation, Data curation, Methodology, Writing - review & editing. **Felix Bachofer**: Conceptualization, Methodology, Validation, Writing - review & editing,

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Supervision, Project administration. **Dominic Sett**: Visualization, Formal analysis, Writing - review & editing. **Nguyen Duc Cuong**: Data curation, Methodology, Writing - review & editing. **Nguyen Dang Giang Chau**: Conceptualization, Methodology, Validation, Writing - review & editing

All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest

REFERENCES

1 J. L. Huntington and R. G. Niswonge, *Water Resour. Res.*, 2012, **48**, W11524.

2 S. E. Manahan, in *Environmental Chemistry*, 2000.

3 World Bank Group (WBG) and Asian Development Bank (ADB), .

4 P. Li, *Environ. Earth Sci.*, 2014, **71**, 4625–4628.

5 M. A. House, *Water Environ. J.*, 1989, **3**, 336–344.

6 D. Chapman, *Water Quality Assessments - A Guide to Use of Biota , Sediments and Water in Environmental Monitoring - Second Edition*, University Press, Cambridge, 2nd edn., 1996.

7 M. A. Al Yousif and A. Chabuk, *J. Ecol. Eng.*, 2023, **24**, 40–55.

8 C. A. Almeida, S. Quintar, P. González and M. A. Mallea, *Environ. Monit. Assess.*, 2007, **133**, 459–465.

9 G. Uddin, S. Nash and A. I. Olbert, *Ecol. Indic.*, 2021, **122**, 107218.

10 S. Chidiac, P. El, N. Ouaini, Y. El, R. Desiree and E. Azzi, *A comprehensive review of water quality indices (WQIs): history , models , attempts and perspectives*, Springer Netherlands, 2025, vol. 22.

11 A. Lumb, T. C. Sharma and J.-F. Bibeault, *Water Qual. Expo. Heal.*, 2011, **3**, 11–24.

12 P. Walsh and W. Wheeler, *Natl. Cent. Environ. Econ.*, 2012, **12–05**, 26.

13 General Department of Environment, 2019.

View Article Online
DOI: 10.1039/D6VA00161K

14 A. D. Sutadian, N. Muttil, A. G. Yilmaz and B. J. C. Perera, *Environ. Monit. Assess.*, 2016, **188**, 1–29.

15 Canadian Council of Ministers of the Environment, *Canadian Council of Ministers of the Environment*, 2017, https://ccme.ca/en/res/wqimanualen.pdf?utm_source=chatgpt.com.

16 E. López-gunn, M. Rica, I. Zugasti, O. Hernaez and M. Pulido-velazquez, 2024, **26**, 1183–1206.

17 P. Praus, *Water*, DOI:doi:10.3390/w11112376.

18 M. Vega, R. Pardo, E. Barrado and L. Debán, *Water Res.*, 1998, **32**, 3581–3592.

19 D. Hammoumi, H. S. Al-aizari, I. A. Alaraidh and M. K. Okla, 2024, 1–22.

20 B. Nath, H. Roy, K. Saidur, F. Mahmud, M. Kamal, M. Hasan, A. K. Bhuiyan, M. Hasan, M. Syed, R. Maksud and S. Islam, *City Environ. Interact.*, 2024, **23**, 100150.

21 M. Kamal, H. Roy, K. Saidur, B. Nath, A. Amin, K. Bhuyan, R. Maksud and S. Islam, *City Environ. Interact.*, 2026, **29**, 100276.

22 WB and ADB, 2020, 32.

23 D. L. T. Anh, N. T. Anh and A. A. Chandio, *Ecol. Inform.*, 2023, **74**, 101960.

24 Viet Nam Ministry of Natural Resources and Environment, 2022, **23**, 1–70.

25 World Bank, *Vietnam's Urbanization at a crossroads*, 2020.

26 H. Vo, 2021, 25.

27 M. K. R. Karen C. Seto, Michail Fragkias, Burak Gu¨ neralp, *PLoS One*, 2011, **6**, e23777.

28 T. T. H. Phan, I. Stiers, T. T. H. Nguyen, T. T. Pham, T. P. Ton, Q. D. Luong and L. Triest, *Bot. Mar.*, 2018, **61**, 213–224.

29 C. T. T. Trang, T. Thanh, T. D. Thanh, V. D. Vinh and T. A. Tu, *Sci. Total Environ.*, DOI:10.1016/j.scitotenv.2020.143130.

30 H. A. Nguyễn, Đ. N. U. Nguyễn and V. H. Huỳnh, *J. Meteorol. Hydrol.*, 2022, 94–102.

31 T. T. T. Cao, H. A. Pham, T. Trịnh, Đ. T. Trần, A. T. Trần and Đ. C. Lê, *J. Mar. Sci. Technol.*, 2014, **14**, 82–88.

32 H. A. Phan, T. Van Le, T. A. Tran and S. H. Nguyen, *Glob. Chang. Sustain. Dev. Asian Emerg. Mark. Econ. Vol. 2*, 2022, 817–841.

33 V. H. Nguyen, V. H. Nguyen, T. K. Truong, P. Nguyen, Ha and D. G. C. Nguyen, *PLoS One*, 2022, **17**, e0274673.

View Article Online
DOI: 10.1039/D6VA00161K

34 P. T. T. Thủy, N. V. Q. Trâm, P. T. H. Cẩm, N. T. D. Hường and T. T. C. Trí, *J. Prev. Med.*, 2021, **31**, 174–180.

35 DONRE (Department of Natural Resources and Environment of Thua Thien Hue province), *Summary report on environmental monitoring results of Thua Thien Hue province in 2020*, 2023.

36 DONRE (Department of Natural Resources and Environment of Thua Thien Hue province), *Summary report on environmental monitoring results of Thua Thien Hue province in 2021*, 2022.

37 N. Van Hop, T. C. To and T. Q. Tung, *ASEAN J. Sci. Technol. Dev.*, 2008, **25**, 435–444.

38 T. Nguyen, *Thua Thien Hue Gazetteer - Natural Section*, Social Sciences Publishing House, 2005.

39 MONRE (Ministry of Natural resource and Environment), 2018.

40 MONRE (Ministry of Natural resource and Environment), 2016.

41 D. K. Lukhabi, P. K. Mensah, N. K. Asare, T. Pulumuka-Kamanga and K. O. Ouma, *Water (Switzerland)*, 2023, **15**, 1–30.

42 J. H. Lee, J. Y. Lee, Y. S. Cha, S. J. Cho, T. H. Kim, Y. K. Cha and J. Y. Koo, *Water Supply*, 2022, **22**, 6338–6355.

43 T. L. Ogden, *Ann. Occup. Hyg.*, 2010, **54**, 255–256.

44 Bộ Tài nguyên và Môi trường (MONRE), *QCVN08:2015/BTNMT, Quy chuẩn kỹ thuật quốc gia về chất lượng nước mặt*, 2015.

45 Vietnam Ministry of Natural Resources and Environment, *QCVN 08:2023/BTNMT: Quy chuẩn kỹ thuật quốc gia về chất lượng nước mặt*, 2023.

46 V. H. Nguyễn, T. Q. Nguyễn, H. P. Nguyễn, V. H. Nguyễn, H. T. Nguyễn, Q. Á. Lê and P. B. Đặng, .

47 Q. V. Dau, K. Kuntiyawichai and A. J. Adeloye, *Environ. Process.*, 2021, **8**, 77–98.

48 M. L. Ahmad Affandi, A. H. M. Din and A. W. Rasib, *Int. J. Remote Sens.*, 2024, **45**, 9033–9063.

49 B. T. nguyên và M. tường (MONRE), *QCVN10:2023/BTNMT, Quy chuẩn kỹ thuật quốc gia về chất lượng nước biển*, 2023.

50 D. Khodyakov, S. Grant, J. Kroger and M. Bauman, *RAND Methodol. Guid. Conduct. Crit. Apprais. Delphi Panels*, DOI:10.7249/tla3082-1.

View Article Online
DOI: 10.1039/D6VA00161K

51 N. McClelland, *US EPA Reg. VII. Kansas City, MO*.

52 T. D. Banda and M. Kumarasamy, *Water (Switzerland)*, DOI:10.3390/W12061534.

53 J. Barbosa Filho and I. B. de Oliveira, *Sci. Rep.*, DOI:10.1038/s41598-021-95912-9.

54 H. M. Joung, W. W. Miller, C. N. Mahannah and J. C. Guitjens, *J. Environ. Qual.*, 1979, **8**, 95–100.

55 Y. Qian, K. W. Migliaccio, Y. Wan and Y. Li, *Water Resour. Res.*, 2007, **43**, 1–10.

56 E. J. Rochelle-Newall, O. Ribolzi, M. Viguier, C. Thammahacksa, N. Silvera, K. Latsachack, R. P. Dinh, P. Naporn, H. T. Sy, B. Soulileuth, N. Hmaimum, P. Sisouvanh, H. Robain, J. L. Janeau, C. Valentin, L. Boithias and A. Pierret, *Sci. Rep.*, 2016, **6**, 1–12.

57 E. Rochelle-Newall, T. M. H. Nguyen, T. P. Q. Le, O. Sengtaheuanghoung and O. Ribolzi, *Front. Microbiol.*, 2015, **6**, 1–15.

58 D. Mushi, G. Kebede, R. B. Linke, A. Lakew, D. S. Hayes, W. Graf and A. H. Farnleitner, *J. Water Health*, 2021, **19**, 575–591.

59 S. Zhao, M. J. Rogers, Y. Liu, G. L. Andersen and J. He, *J. Hazard. Mater.*, 2024, **461**, 132474.

60 C. Wehrheim, M. Lübken, H. Stolpe and M. Wichern, *Water (Switzerland)*, DOI:10.3390/w15071295.

61 T. G. Nguyen, K. A. Phan and T. H. N. Huynh, *Sustain. Environ. Res.*, DOI:10.1186/s42834-022-00156-5.

62 B. Wang, Y. Wang and S. Wang, *Ecol. Indic.*, 2021, **129**, 107931.

63 W. dos S. Carvalho, F. J. C. M. Filho, L. R. Rodrigues and C. S. C. Calheiros, *Appl. Sci.*, DOI:10.3390/app14135666.

64 World Health Organization (WHO), *State of the World's drinking water*, 2022.

65 S. Otieno, L. Cheptegei and S. M. Karume, .

66 I. Essamlali, H. Nhaila and M. El Khaili, *Heliyon*, 2024, **10**, e27920.

67 C. Tsolaki, G. Kokkonis and S. Valsamidis, *Appl. Sci.*, 2026, **16**, 1–33.

View Article Online
DOI: 10.1039/D6VA00161K

Surface-Water Quality Assessment Across a River–Lagoon Continuum in Central Vietnam Using Parameter-Based Analysis, PCA, and VN_WQI

Nguyen Dinh Phuoc[1,2,a], Le Trung Hieu[2,a], Hoang Thai Long[2], Nguyen Van Hop[2], Ho Xuan Anh Vu[2], Felix Bachofer[3], Dominic Sett[4], Nguyen Duc Cuong[5], Nguyen Dang Giang Chau[2]*

All data generated or analyzed during this study are included in this published article and its supplementary information files.