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Organic Pollution Dynamics and WQI Masking Effects in Surface Waters of Lai Chau Province

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Abstract: Composite water quality indices such as the Vietnam Water Quality Index (VN_WQI) are widely used to synthesize complex monitoring data; however, their aggregated structure may obscure environmentally relevant pollution signals. This study evaluates surface water quality in Lai Chau Province, Vietnam, using VN_WQI in combination with component-based, spatial, and scenario-based analyses to examine the representation of organic pollution dynamics. Water quality data from 59 monitoring sites collected during the rainy and dry seasons in 2024 were analyzed using three VN_WQI calculation scenarios, hierarchical cluster analysis (HCA) based on dissolved oxygen (DO), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5), and non-parametric statistical tests. VN_WQI consistently classified surface waters as "Good–Excellent" (95.5–97.6 rainy; 79.4–95.5 dry depending on scenario), yet component-level analysis revealed substantial spatial and seasonal variability. HCA identified three statistically distinct clusters representing different organic pollution regimes that were not apparent from aggregated VN_WQI results. Seasonal analysis showed significant increases in COD and BOD_5 during the dry season ($p < 0.001$), while DO exhibited no significant change. Notably, BOD_5 exceedances reached 86.4% of sites in the dry season despite uniformly high index values. Scenario comparison indicates a trade-off between comprehensiveness and sensitivity. The priority-weighted formulation enhances the detection of organic pollution while retaining the full parameter set, providing a practical approach

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for improving VN_WQI application. These findings support a flexible, context-dependent use of VN_WQI to better identify spatially and seasonally sensitive water-quality risks.

Keywords: VN_WQI; masking effect; organic pollution; spatial analysis; water quality assessment; Lai Chau.

1. Introduction

Surface water quality assessment constitutes a cornerstone of integrated water resources management, as it informs both ecological protection and human use. Composite water quality indices (WQIs) have been widely adopted as practical tools to summarize complex monitoring datasets into a single numerical value that supports decision-making and communication among scientists, managers, and stakeholders. By synthesizing multiple physico-chemical and biological parameters into an aggregated score, WQIs facilitate spatial–temporal comparisons and classification of overall water quality status [1, 2].

The Vietnam Water Quality Index (VN_WQI), promulgated under Decision No. 1460/QĐ-TCMT [3], is based on five groups of parameters: i) pH; ii) Pesticides (e.g., Aldrin, BHC, Dieldrin, DDTs, Heptachlor and its epoxide); iii) Heavy metals (e.g., As, Cd, Pb, Cr^{6+}, Cu, Zn, Hg); iv) Organic and nutrient parameters (e.g., DO, BOD_5, COD, TOC, NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}); and v) Icrobiological indicators (Coliform, E. coli). According to the guideline, VN_WQI calculation requires at least three out of these five groups, with Group IV being mandatory and including at least three parameters. Additional groups (e.g., pesticides or heavy metals) should be included when water bodies are subject to specific pollution sources. These parameters are integrated into a unified scale ranging from 0 to 100. Water quality classes are commonly visualized using color codes (e.g., blue = very good; green = good; yellow = moderate; orange = poor; red = very poor) [3]. While VN_WQI offers a valuable high-level overview of water quality across space and time, its aggregation process inherently involves weighting and averaging, which may obscure variability in individual constituent indicators [2, 4]. Previous applications of WQI in Vietnam have largely emphasized overall classification of water quality in riverine and coastal systems, with limited attention to the potential masking of spatially and seasonally sensitive organic pollution signals [5, 6].

Despite their widespread use, composite water quality indices are inherently sensitive to parameter selection and weighting schemes. This flexibility, while practical, may influence the responsiveness of VN_WQI to specific pollution signals. In particular, organic pollution indicators such as dissolved oxygen (DO), chemical oxygen demand (COD), and biochemical oxygen demand (BOD_5) exhibit strong spatial and seasonal variability, but their influence on the aggregated index may be attenuated when combined with more stable parameters.

Given this methodological context, there is a need to explicitly evaluate how alternative VN_WQI calculation configurations affect the representation of organic pollution dynamics. Accordingly, this study combines VN_WQI calculation with hierarchical cluster analysis, spatial pattern analysis, and seasonal statistical testing, and further incorporates a comparative assessment of three calculation scenarios: i) A baseline scenario using the full parameter set; ii) A priority-weighted scenario emphasizing organic and nutrient parameters; and iii) A reduced-parameter scenario excluding stable background parameters while maintaining the required parameter-group structure.

This integrated framework is designed to: i) Assess how different VN_WQI calculation scenarios affect the ability of the index to capture key spatial and seasonal dynamics of organic pollution in Lai Chau Province; and ii) Identify environmentally sensitive areas and periods that may be overlooked by conventional composite index assessments.

2. Materials and Methods

2.1. Study Area

The study was conducted in Lai Chau Province, located in northwestern Vietnam, a mountainous region characterized by steep terrain, deeply incised river valleys, and a complex river network. The province encompasses a mixture of upstream headwater catchments, urban wards, township centers, and predominantly rural agricultural areas. These physiographic and socio-environmental conditions create pronounced spatial heterogeneity in hydrological processes, land–water interactions, and the sensitivity of surface waters to organic pollution.

Surface waters in Lai Chau are generally considered to have high baseline quality due to limited industrial development; however, localized pressures from domestic wastewater discharge, agricultural runoff, and hydrological alteration persist and vary markedly across space and season [7]. This setting therefore provides a suitable case for examining whether composite water quality indices, such as the VN_WQI, can adequately capture localized and seasonally amplified organic pollution signals under generally favorable background conditions, as well as for evaluating how different VN_WQI calculation configurations influence the detection of such signals.

2.2. Water Quality Monitoring Data

Water quality data were obtained from the provincial surface-water monitoring program conducted by the Lai Chau Department of Agriculture and Rural Development in 2024. The dataset comprises 59 fixed monitoring sites distributed across major river reaches, tributaries, lakes, and canals, representing a wide range of hydrological and land-use settings within the province.

Sampling was carried out during two monitoring campaigns representing contrasting hydrological conditions: i) The rainy season (June 2024); and ii) The dry season (December 2024).

A total of 17 water quality parameters were measured and used to calculate the Vietnam Water Quality Index (VN_WQI) in accordance with Decision No. 1460/QĐ-TCMT [3]. These parameters include Group I (pH), Group II (Cr^{6+}, As, Cu, Zn, Pb), Group III (DDTs, Aldrin, and Dieldrin), Group IV (DO, COD, BOD_5, NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}) and Group V (total coliforms).

The dataset covers all major VN_WQI parameter groups and is structured to support multiple calculation scenarios. All scenarios were constructed from the same dataset while ensuring compliance with the guideline requirement of including Group IV parameters in the VN_WQI calculation.

All laboratory analyses were conducted in accordance with Vietnamese national standard methods. Water quality was evaluated against the National Technical Regulation on Surface Water Quality (QCVN 08:2023/BTNMT)[1], with particular reference to Grade B (moderate water quality), defined by threshold values of DO ≥ 5.0 mg L^{-1}, COD ≤ 15 mg L^{-1}, and BOD_5 ≤ 6 mg L^{-1}.

2.3. VN_WQI Calculation and Component-based Analysis

The VN_WQI was calculated following Decision No. 1460/QĐ-TCMT [3], in which parameter sub-indices are aggregated at the group level and combined into a final index.

Three calculation scenarios were implemented using the corresponding formulations:

Scenario 1 (Full formulation; Applied to all parameters from Groups I–V):

[1] The VN_WQI follows Decision No. 1460/QĐ-TCMT (based on QCVN 08:2015), while parameter-level evaluation refers to QCVN 08:2023/BTNMT. Differences in threshold values are minor and do not affect the comparative analysis, as exceedances are interpreted to indicate relative patterns.

$$WQI = \frac{WQI_I}{100} \times \frac{\left(\prod_{i=1}^{n} WQI_{II}\right)^{1/n}}{100} \times \frac{\left(\prod_{i=1}^{m} WQI_{III}\right)^{1/m}}{100} \times \left[\frac{1}{k}\sum_{i=1}^{k} WQI_{IV} \times \frac{1}{l}\sum_{i=1}^{l} WQI_{V}\right]^{1/2} \quad \text{(Eq. 1)},$$

where $WQI_I, WQI_{II}, WQI_{III}, WQI_{IV}, WQI_V$ are the sub-indices of parameter Groups I–V, respectively

Scenario 2 (Priority weighting; Applied to the same parameter set, increasing the influence of Group IV:

$$WQI = \frac{WQI_I}{100} \times \frac{\left(\prod_{i=1}^{n} WQI_{II}\right)^{1/n}}{100} \times \frac{\left(\prod_{i=1}^{m} WQI_{III}\right)^{1/m}}{100} \times \left[\left(\frac{1}{k}\sum_{i=1}^{k} WQI_{IV}\right)^2 \times \left(\frac{1}{l}\sum_{i=1}^{l} WQI_{V}\right)\right]^{1/3} \quad \text{(Eq. 2)}$$

Scenario 3 (Reduced formulation): Applied by retaining the minimum required parameter groups (≥3), including the mandatory Group IV with at least three parameters (DO, BOD_5, and COD). In accordance with regulatory provisions [3] requiring the inclusion of Groups II and III for water bodies affected by pesticide and heavy metal pollution, and given that the monitoring dataset covers diverse water bodies across the province with varying impact conditions, these groups were retained, while Group I (pH) and Group V (microbiological indicators) were excluded:

$$WQI = \frac{\left(\prod_{i=1}^{n} WQI_{II}\right)^{1/n}}{100} \times \frac{\left(\prod_{i=1}^{m} WQI_{III}\right)^{1/m}}{100} \times \left(\frac{1}{k}\sum_{i=1}^{k} WQI_{IV}\right) \quad \text{(Eq. 2)}$$

In addition to the aggregated VN_WQI, 17 component-level sub-indices were analyzed to examine potential masking effects within the composite index.

2.4. Spatial Datasets and GIS Processing

Spatial analyses were conducted within a geographic information system (GIS) framework. To characterize the spatial distribution of water quality and to interpret potential controlling factors, following Ngo et al., [7] and Chen & Lu [8], the following spatial datasets were employed.

- Hydrological and administrative boundary maps (2025), including commune-level population attributes provided by the Lai Chau Department of Agriculture and Environment;

- A land use land cover map (2023) derived from the Global PALSAR-2/ALOS-2 Land Cover dataset provided by JAXA [9], comprising water bodies, built-up areas, rice fields, other agricultural land, grass/shrub, woody crops, barren land, deciduous forest, evergreen forest, and plantation forest;

- A digital elevation model (DEM; SRTM 1 Arc-Second Global), from which terrain slope was derived;

- Geographic coordinates of the 59 monitoring sites.

These variables were not used to directly quantify pollution sources; instead, they serve as proxies for environmental conditions influencing pollutant generation, transport, and dilution, consistent with previous studies [8, 10, 11].

To ensure adequate sample sizes for statistical analysis and to facilitate interpretation of spatial controls on organic pollution, the original land-cover classes were aggregated into three dominant categories reflecting contrasting hydrological and pollution processes: i) Built-up areas; ii) Open agricultural land; and iii) Woody vegetation (including forests and tree crops).

Terrain slope was classified into two groups (≤5% and >5%) to distinguish relatively flat areas from steeper, hydrologically dynamic settings. Population density was categorized into three classes (<50, 50–100, and >100 persons km^{-2}) to represent varying levels of anthropogenic pressure.

Buffer zones were generated around each monitoring site to extract spatial attributes: 100 m for slope, 500 m for dominant land cover, and 1000 m for population density. These spatial attributes were subsequently linked to water-quality observations for statistical and cluster-based analyses.

2.5. Spatial Clustering and Statistical Analysis

Spatial differentiation of organic pollution was examined using hierarchical cluster analysis (HCA) based on DO, COD and BOD_5 measured during both monitoring seasons. HCA was performed using Ward's linkage method and Euclidean distance to minimize within-cluster variance. A phenon line was selected at a rescaled distance that maximized within-cluster similarity while maintaining clear separation among clusters, resulting in three distinct groups of monitoring sites.

Discriminant analysis (DA) was subsequently applied to evaluate the robustness of the HCA results and to assess the accuracy of site classification among clusters.

Seasonal differences between the rainy and dry seasons were assessed using the Wilcoxon signed-rank test due to the non-normal distribution of several water quality parameters.

Spatial differences associated with landscape and anthropogenic factors, including slope, land cover, population density, and flow type, were evaluated using the Mann–Whitney U test.

In addition, exceedances of the national surface water quality standard (QCVN 08:2023/BTNMT) were quantified for DO, COD, and BOD_5 to identify environmentally sensitive areas and periods of elevated organic pollution risk.

2.6. Analytical Framework for Identifying Masking Effects

The masking effect of the VN_WQI was evaluated using an integrated analytical framework designed to contrast aggregated index outcomes with parameter-level behavior. The framework consists of four main steps:

i) Comparison between aggregated VN_WQI classifications and the component-level behavior of DO, COD, and BOD_5;

ii) Comparison between aggregated VN_WQI classifications and the component-level behavior of Identification of monitoring sites where organic pollution indicators exhibit degradation or regulatory exceedances despite consistently high VN_WQI scores;

iii) Comparison between aggregated VN_WQI classifications and the component-level behavior of Spatial clustering and mapping of these sites to reveal spatial patterns not captured by the composite index;

iv) Comparison between aggregated VN_WQI classifications and the component-level behavior of Seasonal analysis to assess whether hydrological conditions amplify discrepancies between VN_WQI classifications and organic pollution signals.

This framework enables a systematic assessment of whether and how the VN_WQI obscures localized and seasonally amplified organic pollution dynamics under conditions of generally high baseline water quality.

3. Results and Discussion

3.1. VN_WQI-based Overview: Apparent Stability at the Provincial Scale

3.1.1. Provincial-scale VN_WQI Overview

Based on the 2024 surface-water monitoring program encompassing 59 sites across Lai Chau Province, the aggregated VN_WQI indicates generally high surface-water quality at the provincial scale.

Across the three calculation scenarios, mean VN_WQI values remained within the "Good" to "Excellent" categories, with Scenario 1 (full formulation) yielding average values of 97.6 (rainy season) and 95.5 (dry season), Scenario 2 (priority weighting) slightly lower values of 96.8 and 94.0, and Scenario 3 (reduced formulation) markedly lower values of 89.0 and 79.4, respectively.

VN_WQI values predominantly fall within the "Good" to "Excellent" categories (91–100) in both the rainy and dry seasons under Scenarios 1 and 2, with most monitoring sites consistently achieving scores above 95. Spatially, VN_WQI values exhibit a relatively narrow range across the monitoring network, with sites located in different sub-basins, hydrological settings, and land-use contexts displaying comparable index scores and no clearly defined provincial-scale zones of degraded water quality.

In contrast, Scenario 3 produces a wider range of VN_WQI values and a noticeable decline in the dry season, suggesting enhanced sensitivity of the index when stable background parameters are excluded.

Seasonal variation in VN_WQI is observable at individual monitoring sites; however, under Scenarios 1 and 2, these changes are typically insufficient to alter the overall classification category assigned by the index. Consequently, seasonal hydrological contrasts are only weakly expressed in the aggregated VN_WQI results.

The divergence observed in Scenario 3 highlights the influence of parameter selection on index responsiveness, indicating that the apparent provincial-scale stability is partly dependent on the inclusion of parameters with consistently high scores.

While this assessment conveys an image of stable and favorable surface-water conditions across Lai Chau Province, the composite nature of VN_WQI warrants closer examination at the parameter level to determine whether localized or seasonally sensitive water-quality signals may be obscured. This issue is explored through a component-wise analysis of VN_WQI in the following subsection.

3.1.2. Component-wise Heterogeneity within the VN_WQI Framework

To examine the internal structure of the aggregated VN_WQI, a component-wise visualization of individual WQI scores was constructed for all monitoring sites and parameters (Figure 1). This analysis is presented for Scenario 1 (full formulation), which represents the standard VN_WQI configuration and serves as the basis for evaluating potential masking effects. The resulting heatmap reveals a clear contrast between parameters that consistently attain maximum scores and those exhibiting pronounced variability.

Heavy metals, nutrients, pesticide residues, and pH display uniformly high component scores across all sites and both seasons, reflecting concentrations that remain well within regulatory limits. In contrast, DO, COD, and BOD_5 exhibit noticeable spatial and seasonal fluctuations, with several sites characterized by lower component WQI classes despite uniformly high aggregated VN_WQI values.

This internal imbalance indicates that variability in organic pollution indicators is effectively diluted within the composite index by the dominance of parameters that consistently score at the maximum level. Consequently, the aggregated VN_WQI conveys an appearance of homogeneous and stable water quality, whereas parameter-level analysis reveals the presence of localized and seasonally sensitive organic pollution signals. This pattern is consistent with the high VN_WQI values observed under Scenarios 1 and 2 (Section 3.1.1), and helps explain the increased sensitivity of Scenario 3 when selected stable parameters are excluded.

Similar masking effects associated with composite water quality indices have been reported in previous studies, particularly in regions characterized by generally good baseline water quality. Chidiac et al., [2] emphasized that parameters with consistently low concentrations, such as heavy metals and pesticide residues, tend to dominate composite indices and reduce their sensitivity to indicators that exhibit stronger spatial or seasonal variability. Likewise, Uddin et al., [4] demonstrated that conventional WQI formulations may underrepresent organic pollution dynamics when stable parameters receive equal or greater weighting than more responsive indicators. The component-wise patterns observed in Lai Chau Province are fully consistent with these findings, confirming that VN_WQI behaves similarly to other composite indices in masking localized organic pollution signals under favorable background conditions.

3.2. Spatial Differentiation of Organic Pollution Revealed by Component-based Analysis

3.2.1. Spatial Clustering of Monitoring Sites Based on Organic Pollution Indicators

To investigate whether the apparent spatial uniformity suggested by the aggregated VN_WQI conceals underlying heterogeneity, HCA was performed using DO, COD, and BOD_5

data from both the rainy and dry seasons. These parameters were selected because they represent the most sensitive indicators of organic pollution and exhibit the greatest variability in the component-wise VN_WQI results (Section 3.1.2).

The resulting HCA dendrogram shows a clear separation of the 59 monitoring sites into three distinct clusters when a phenon line is applied at a rescaled distance of 12.5 (Figure 2). This cut-off was selected because it provides an appropriate balance between within-cluster homogeneity and between-cluster heterogeneity, allowing meaningful interpretation of spatial differences in organic pollution characteristics.

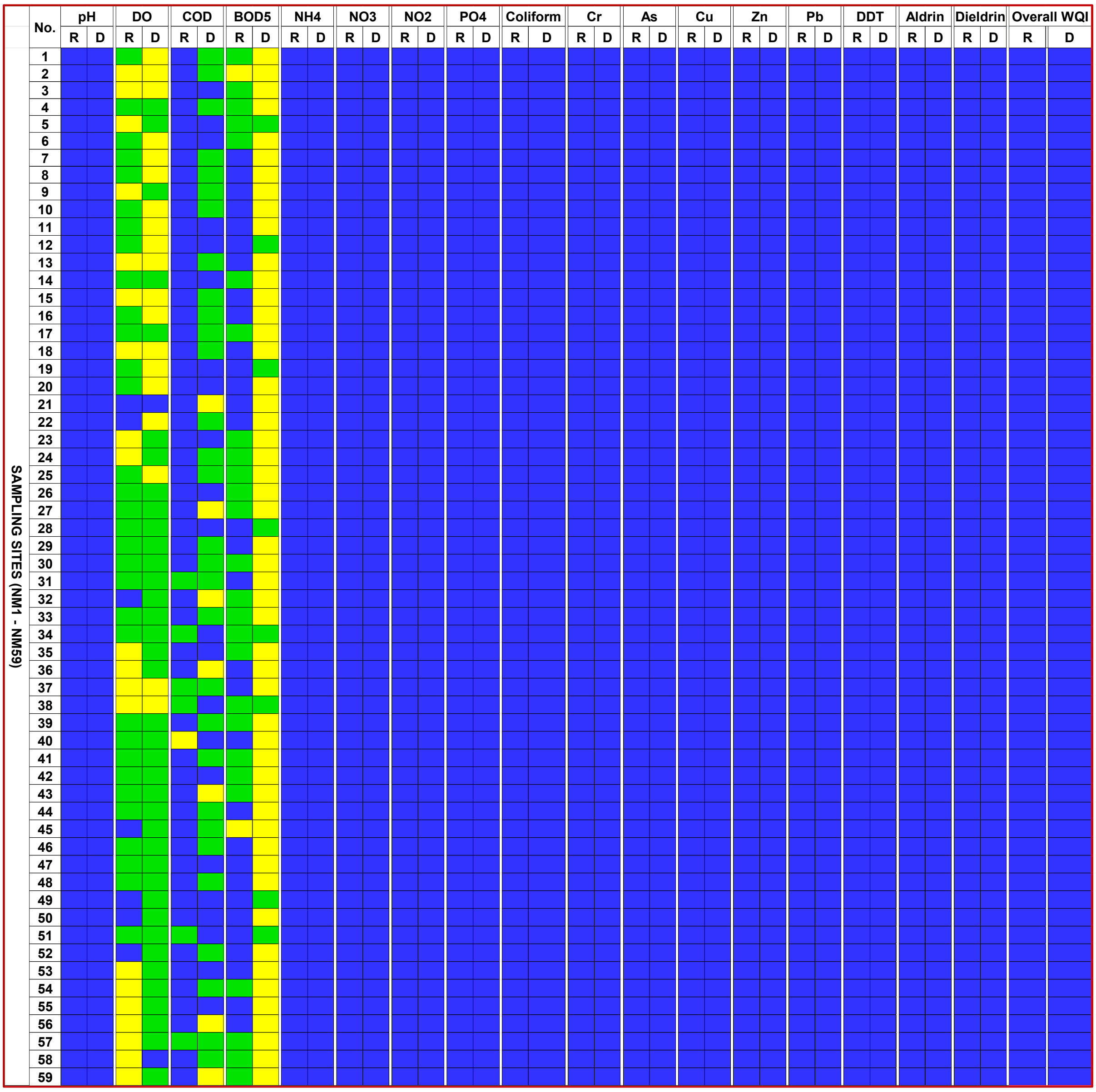

Figure 1. Component-wise water quality classifications based on the VN_WQI for Scenario 1 (full formulation) across 59 monitoring sites in Lai Chau Province (2024).

Note: The heatmap is designed to highlight relative patterns and contrasts among parameters using color gradients rather than exact numerical values; R: rainy season; D: dry season.

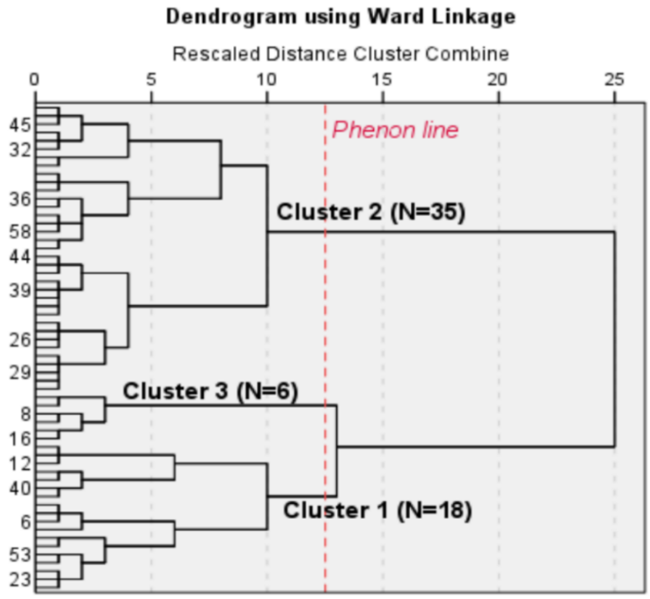

Figure 2. Dendrogram of 59 monitoring sites based on DO, COD, and BOD_5 across rainy and dry seasons.

The robustness of the clustering results was further evaluated using discriminant analysis (DA). The DA achieved an overall classification accuracy of 89.8%, and all discriminant functions were statistically significant ($p<0.001$), confirming the reliability of the cluster structure derived from the HCA. Examination of the structure matrix indicates that DO and COD contribute most strongly to discrimination among clusters, particularly under dry-season conditions, highlighting the importance of low-flow periods in differentiating organic pollution regimes.

The identification of three statistically distinct clusters indicates that spatially coherent patterns of organic pollution exist across the monitoring network. These patterns are not evident in the aggregated VN_WQI results, where overall water quality appears relatively uniform (Section 3.1.2), thereby supporting the interpretation that composite indices may mask underlying variability in sensitive parameters.

The identification of three statistically distinct clusters demonstrates that, despite uniformly high VN_WQI scores at the provincial scale, monitoring sites exhibit pronounced spatial differentiation when assessed using organic pollution indicators. This finding provides clear evidence that spatially coherent patterns of water-quality variation exist but are not captured by the aggregated VN_WQI, thereby justifying further cluster-based characterization and spatial interpretation in subsequent sections.

3.2.2. Cluster-based Characterization of Organic Pollution Dynamics

The three clusters identified by HCA represent distinct organic pollution regimes with consistent seasonal behavior and clear spatial differentiation across Lai Chau Province. These patterns are derived from indicator distributions and spatial arrangement of monitoring sites, and together reflect different dominant processes controlling organic pollution dynamics.

In the rainy season, Cluster 1 exhibits higher COD and BOD_5 concentrations compared with Clusters 2 and 3, accompanied by relatively lower DO levels (Figure 3). This pattern indicates a strong influence of rainfall-driven surface runoff, whereby organic matter accumulated on land surfaces is mobilized and transported into surface waters during high-flow conditions. In contrast, Cluster 3 shows the most favorable water-quality conditions in the rainy season, with higher DO and lower COD and BOD_5, suggesting effective dilution and natural re-aeration under well-oxygenated flow conditions. Cluster 2 generally presents intermediate conditions during the rainy season, with moderate levels of organic pollution indicators.

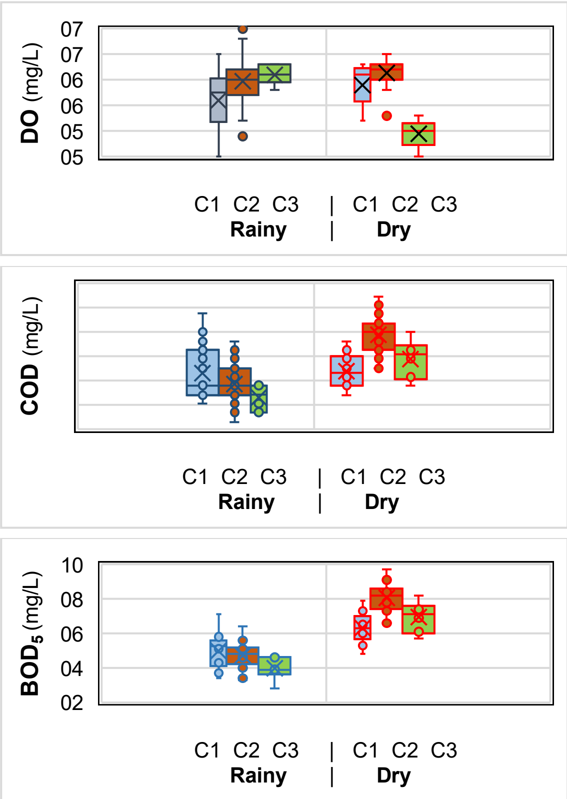

Figure 3. Boxplots of DO, COD, and BOD_5 across the three HCA clusters (C1, C2, C3) in the rainy and dry seasons.

During the dry season, inter-cluster contrasts become more pronounced but shift in dominance. Cluster 2 shows markedly higher COD and BOD_5 concentrations than the other clusters, indicating the increasing influence of continuous point-source inputs under reduced flow conditions and limited dilution capacity. Cluster 1, by contrast, exhibits relatively low COD and BOD_5 during the dry season, consistent with the absence of rainfall-driven runoff. Cluster 3 is characterized by a pronounced reduction in DO during the dry season, despite only moderate COD and BOD_5 levels, suggesting that oxygen dynamics may be influenced by hydrological conditions associated with low-flow periods rather than organic loading alone. However, the roles of slope and flow regime are not statistically significant (Table 1, $p > 0.05$), indicating that these factors cannot be conclusively identified as primary drivers based on the current dataset.

Spatially, Cluster 1 sites are frequently associated with agricultural or mixed land-cover areas, where diffuse runoff processes are likely dominant (Figure 4). Cluster 2 is concentrated in urban wards, township centers, and densely populated corridors, consistent with the influence of continuous wastewater inputs. Cluster 3 is mainly located in upstream reaches, steeper terrain, and semi-enclosed or hydrologically sensitive areas, where flow regime and reaeration processes strongly regulate dissolved oxygen conditions.

These spatial associations should be interpreted as indicative relationships rather than direct causal attribution, as land cover, population density, and terrain are used here as proxies for environmental conditions. Overall, the combined seasonal and spatial patterns confirm that each cluster represents a distinct organic pollution regime governed by different dominant mechanisms, including runoff-driven non-point inputs (Cluster 1), point-source loading modulated by dilution (Cluster 2), and flow-regulated oxygen dynamics (Cluster 3).

Importantly, such process-based differentiation is not captured by the aggregated VN_WQI, which masks underlying heterogeneity across clusters. Similar mechanisms have been widely reported in previous studies, where non-point source pollution dominates under high-flow conditions, point-source impacts intensify during low-flow periods, and dissolved oxygen dynamics in upstream systems are primarily controlled by hydrological conditions [12-14]. The consistency between these established mechanisms and the observed patterns in Lai Chau supports the robustness of the cluster-based interpretation.

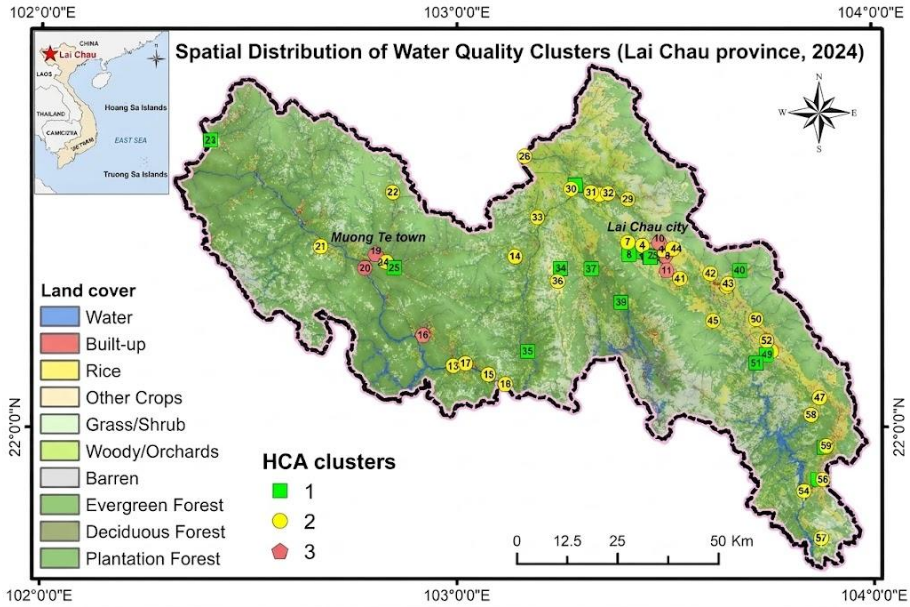

Figure 4. Spatial distribution of monitoring sites by HCA-derived cluster.

3.3. Identification of Sensitive Areas and Controlling Factors

3.3.1. Spatial Patterns of Standard Exceedances of Organic Pollution Indicators

Spatial patterns of organic pollution were evaluated based on exceedances of the national surface water quality standard (QCVN 08:2023/BTNMT) for DO, COD, and BOD_5. Among these indicators, BOD_5 shows the highest sensitivity to localized stress, with exceedance rates reaching 86.4% in the dry season, compared to 3.4% in the rainy season. COD exceedances are limited during the rainy season (1.7%) but increase markedly under dry-season low-flow conditions (11.9%), while DO exceedances occur sporadically in both seasons (Figure 5).

Exceedance events exhibit clear spatial structuring and are not randomly distributed across the monitoring network. Dry-season COD exceedances are exclusively associated with Cluster 2, reflecting continuous anthropogenic inputs under reduced dilution capacity. BOD_5 exceedances are concentrated in urban and peri-urban locations, including drainage channels and low-flow reaches, indicating persistent organic loading during the dry season. In contrast, DO exceedances are more dispersed, occurring in runoff-influenced settings during the rainy season and hydrologically sensitive sites during the dry season.

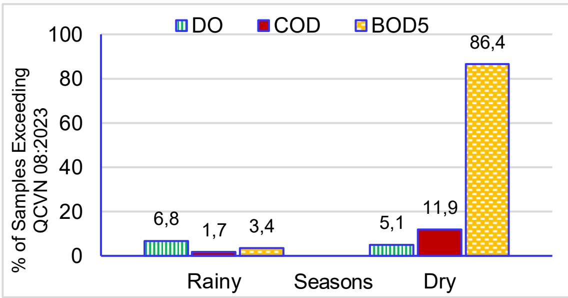

Figure 5. Seasonal exceedance rates of DO, COD, and BOD_5 relative to QCVN 08:2023/BTNMT.

The clustering of standard exceedances within specific spatial groups and seasons indicates that organic pollution risks in Lai Chau are both spatially and temporally structured. These patterns reflect unevenly distributed pollution pressures across sites and seasons. These patterns remain largely undetected by the aggregated VN_WQI, which consistently classifies the same sites as “Good” or

"Excellent." Consequently, exceedance-based analysis provides a critical complement to VN_WQI, enabling the identification of environmentally sensitive areas and periods of elevated organic pollution risk.

3.3.2. Influence of Landscape and Anthropogenic Factors on Organic Pollution Sensitivity

To further elucidate the controls underlying the observed spatial patterns of organic pollution, non-parametric Mann–Whitney U tests were applied to examine the influence of key landscape and anthropogenic factors on DO, COD, and BOD_5. The results (Table 1) indicate that the observed spatial variability in organic pollution indicators is associated with specific environmental contexts.

Topographic effects are most pronounced during the dry season. Monitoring sites located in low-slope areas (≤5%) exhibit significantly higher COD and BOD_5 concentrations ($p < 0.05$), suggesting an association with reduced flow velocity and potential accumulation of organic matter under low-flow conditions. However, slope itself does not show consistent statistical significance across all parameters and seasons.

Table 1. Statistical significance (p-value) of landscape and anthropogenic factors influencing organic pollution indicators

Factor	DO–rainy	DO–dry	COD–rainy	COD–dry	BOD_5–rainy	BOD_5–dry
Slope	0.565 (ns)	0.681 (ns)	0.831 (ns)	0.021 (*)	0.056 (ns)	0.032 (*)
Population density	0.232 (ns)	0.010 (**)	0.034 (*)	0.347 (ns)	0.701 (ns)	0.480 (ns)
Land cover	0.238 (ns)	0.513 (ns)	0.230 (ns)	0.122 (ns)	0.002 (*)	0.088 (ns)
Flow type	0.138 (ns)	0.917 (ns)	0.262 (ns)	0.011 (*)	0.571 (ns)	0.005 (**)

Note: *p*-values derived from Mann–Whitney U tests; ns = not significant;
* significant at $p < 0.05$; ** significant at $p < 0.01$.

Anthropogenic pressure, represented by population density, shows a significant association with organic pollution indicators. Higher population density is linked to lower DO concentrations during the dry season and elevated COD during the rainy season ($p < 0.05$), indicating a possible influence of wastewater inputs and runoff processes.

Hydrological setting further modulates organic pollution sensitivity. Flow type is significantly associated with dry-season COD and BOD_5 ($p < 0.05$), suggesting that low-flow and semi-lentic conditions may favor the accumulation of oxygen-demanding substances. In addition, land-cover contrasts reveal significantly higher rainy-season BOD_5 in agricultural and built-up areas compared with forest-dominated landscapes ($p < 0.05$), indicating the influence of surface runoff processes.

Overall, these statistically significant associations provide supporting evidence for the spatial differentiation identified in the HCA, suggesting that the observed patterns are linked to interacting landscape, hydrological, and anthropogenic factors. These results should be interpreted as indicative relationships rather than definitive causal mechanisms. Such context-dependent sensitivities remain largely undetected when surface-water quality is assessed using the aggregated VN_WQI alone.

3.4. Seasonal Amplification of Organic Pollution Signals and Implications for VN_WQI Interpretation

3.4.1. Seasonal Dynamics and Amplification of Organic Pollution Signals

Seasonal contrasts in organic pollution indicators were evaluated using paired rainy- and dry-season observations to assess whether hydrological seasonality generates variations in pollution signals that are not fully captured by the aggregated VN_WQI. The Wilcoxon signed-rank test indicates that COD and BOD_5 exhibit significant seasonal variation ($p < 0.001$), whereas DO shows no statistically significant difference between seasons ($p = 0.393$).

As illustrated by cluster-wise distributions (Figure 3), COD and BOD_5 are consistently higher during the dry season, reflecting increased organic concentrations under reduced flow and limited dilution capacity. In contrast, DO shows strong spatial variability without a consistent seasonal trend, suggesting that oxygen dynamics are influenced by both local hydrological and morphological conditions rather than seasonal forcing alone.

This seasonal asymmetry is further confirmed by exceedance analysis (Figure 5), where dry-season exceedance rates increase markedly to 11.9% for COD and 86.4% for BOD_5, compared with 1.7% and 3.4% in the rainy season, respectively. Despite this clear seasonal amplification of organic pollution signals, aggregated VN_WQI classifications remain largely stable across seasons, indicating a relatively limited responsiveness of the composite index to seasonal variability in organic-related indicators.

From a management perspective, this suggests that reliance on VN_WQI alone may underestimate potential deterioration of water quality during low-flow periods, when dilution capacity is reduced and aquatic systems are more vulnerable to organic loading. Therefore, seasonally targeted assessments that emphasize DO, COD, and BOD_5 can improve detection of dry-season water-quality risks.

3.4.2. Interpretation of VN_WQI Behavior and Implications for Water Quality Assessment

The observed seasonal discrepancy suggests that VN_WQI may exhibit reduced sensitivity to variations in organic pollution indicators under generally high baseline water-quality conditions. This arises from the structure of the composite index, where parameters that remain relatively stable or consistently meet good-quality thresholds (e.g., certain metals, nutrients, or pesticides in this dataset) tend to dominate the overall score, thereby diminishing the relative influence of more dynamic indicators such as DO, COD, and BOD_5.

This behavior helps explain why VN_WQI indicates relatively uniform and favorable water quality across Lai Chau Province despite: (i) clear spatial clustering patterns (Section 3.2), (ii) pronounced dry-season amplification of organic indicators (Section 3.4.1), and (iii) observed exceedances of organic standards (Section 3.3). Similar limitations of composite WQI approaches have been widely reported, where aggregated indices show limited responsiveness to localized organic and nutrient pollution under variable hydrological conditions [12-14]. Comparable findings in Vietnam, including studies in the coastal waters of Hai Phong and the Cau River basin, also indicate that WQI-based assessments may smooth out local-scale pollution signals under urban influence and low-flow conditions [5, 6].

These consistent observations suggest that this behavior reflects a known characteristic of composite index-based water quality assessment rather than a site-specific anomaly.

The flexibility embedded in Decision No. 1460/QĐ-TCMT provides a practical framework for methodological adjustment. The comparison of three calculation scenarios reveals a trade-off between comprehensiveness and sensitivity. The full formulation (Scenario 1) ensures comprehensive representation of water quality but shows limited responsiveness to spatial and seasonal variability. The priority-weighted formulation (Scenario 2), which increases the contribution of DO, COD, and BOD_5, improves sensitivity to organic pollution while maintaining consistency with the standard VN_WQI framework. The reduced formulation (Scenario 3) further enhances sensitivity but reduces representativeness of overall water quality conditions.

Among these, Scenario 2 provides the most balanced and operationally feasible approach, as it improves detection of dry-season organic pollution and spatial differentiation while preserving methodological consistency and data completeness.

Overall, while VN_WQI remains appropriate for broad-scale communication of water quality status, its diagnostic capability can be strengthened through a context-dependent application strategy. For routine assessment, the standard formulation may be retained. However, for targeted analysis—particularly during dry-season conditions or in environmentally sensitive areas identified in this study (urban corridors and upstream hydrologically sensitive zones)—the use of organic-priority weighting or selective emphasis on DO, COD, and BOD_5 is recommended. This integrated approach enhances the sensitivity of VN_WQI without compromising its standardized framework, thereby improving identification and prioritization of organic pollution risks in regions characterized by generally good but spatially and seasonally heterogeneous water quality conditions.

4. Conclusion

Across 59 monitoring sites in Lai Chau Province, this study reveals a clear discrepancy between aggregated VN_WQI results and underlying organic pollution dynamics. While VN_WQI consistently classifies surface water as "Good–Excellent," detailed analysis identifies three statistically distinct spatial clusters and a pronounced seasonal contrast, with BOD_5 exceedances reaching 86.4% of sites during the dry season. These findings demonstrate that substantial spatial differentiation and seasonal deterioration can occur without being clearly reflected in the composite index.

This mismatch arises from the aggregation structure of VN_WQI, in which parameters that consistently achieve high scores reduce the relative influence of more variable indicators such as DO, COD, and BOD_5. As a result, spatial clustering, seasonal contrasts, and exceedance patterns identified in this study are only partially represented in the overall index values.

The scenario-based analysis highlights a practical pathway to address this limitation. The full formulation maintains consistency with the standard framework but shows limited responsiveness to organic pollution dynamics. The reduced formulation increases sensitivity but excludes part of the monitoring information. In contrast, the priority-weighted approach, which emphasizes DO, COD, and BOD_5, improves the detection of spatial and seasonal variability while retaining the full parameter set.

From a management perspective, a flexible application of VN_WQI is recommended. The standard formulation remains suitable for routine provincial reporting. However, during the dry season and in environmentally sensitive areas corresponding to the identified spatial clusters, greater emphasis on organic indicators or the application of priority weighting provides a more effective basis for detecting and prioritizing water-quality risks. This approach enhances the practical utility of VN_WQI while remaining consistent with the existing regulatory framework.

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