

Reach-scale pollution gradients and seasonal snapshots of water quality along the Nhue River, Vietnam: integrating multivariate analysis and VN-WQI

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Research Article

Keywords: Nhue River, urban river pollution, spatial gradient, VN-WQI, principal component analysis, hierarchical clustering

Posted Date: September 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10830926/v1>

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Additional Declarations: No competing interests reported.

Abstract

This study characterizes reach-scale pollution gradients and two seasonal water-quality snapshots from an urban river heavily impacted by wastewater in northern Vietnam. At 12 stations, the physicochemical, organic, nutrient, microbial, and metal attributes of water samples were analyzed during one dry-season (DS) and one rainy-season (RS) campaign. Due to the lack of within-season replicates, the comparison of DS-RS results is descriptive. An organic-nutrient-microbial gradient was observed across R2-R7. At the reach scale, median dissolved oxygen (DO), biochemical oxygen demand (BOD5), ammonium (NH₄⁺), and phosphate (PO₄³⁻) were 1.76, 42.7, 23.0, and 5.77 mg/L in DS and 2.65, 19.5, 10.0, and 3.82 mg/L in RS. While some indices decreased downstream, the overall water quality was poor to very heavily polluted according to the VN-WQI. BOD5, total suspended solids (TSS), NH₄⁺, PO₄³⁻, and total coliforms were positively correlated ($p < 0.05$). With eight variables, the PCA revealed that PC1 and PC2 accounted for 62.0 and 17.2% of variance, respectively, and the HCA highlighted the R2-R7 cluster as distinct from the transitional and downstream reaches. Metals were generally poorly distributed, providing limited complementarity to the other variables. The study demonstrates that the combined use of an aggregate water-quality index and multivariate analysis effectively identifies pollution gradients in urban rivers with limited data. Whereas the VN-WQI served as an overarching assessment of the system's ecological integrity, the reach-scale trends and PCA scores highlighted management priorities. This approach can be applied to other urbanized catchments impacted by wastewater.

1. Introduction

Urban rivers in developing urbanized areas are subject to diverse and interacting inputs from domestic, industrial, and traditional productive sectors, as well as from agricultural sectors, particularly in tropical urbanizing areas. These multiple stresses are more likely to generate simultaneous changes in oxygen consumption, nutrients, Suspended Particulate Matter (SPM), ions, and microbial indicators. In addition, in tropical urbanizing areas, the domestic and industrial waste water is frequently inadequately intercepted and treated and the river flow is highly variable throughout the year due to the monsoons (Hoque et al., 2021; Kookana et al., 2020). Recent studies in intensively populated tropical regions provide additional evidence that hydroclimatic variations may modify the magnitude of BOD, nutrients, solids, and coliform loads, whereas urban land use class was associated with high levels of pollutants throughout the year (Porto et al., 2026).

Hydrological variability may both dilute and flush pollutants from a watercourse, and thus, one cannot expect cleaner water downstream, simply because it has rained. An increased flow of water will decrease the concentration of wastewaters dissolved substances and oxygen-consuming capacity of water, whereas the content of suspended matter, nutrients, and microorganisms in the river or stream may increase (Alkhadher et al., 2025; Porto et al., 2026). In Vietnam, recent assessments of the Huong River–Tam Giang continuum also identified that the changes were not uniform throughout the system but rather occurred in distinct areas with significant impacts on hydronomic processes (Nguyen et al., 2026). This indicates that the pollution levels can be analyzed from two perspectives: the extent of

contamination in relation to the entire river and the differences in the impact between the particular snapshots.

The Nhue River is an interesting case because it serves as both a drainage channel and a sewer for the wastewater of Hanoi, while also providing water to farms downstream which rely on its resources. Previous research has indicated that this area suffers from significant oxygen depletion and severe organic and nutrient pollution in the waters of Hanoi. (Hanh et al., 2010; Trinh Anh et al., 2006), fecal contamination linked predominantly to human activities (Mai Tanaka et al., 2018), and spatial differentiation in conventional water-quality variables using multivariate analysis (Hue & Thanh, 2020). More recent work has broadened the concern to emerging contaminants (Phung et al., 2022) and to metal accumulation in sediment and biota, where ecological and human-health risks may persist even when the instantaneous water-column signal is less pronounced (Ngo et al., 2021). Monitoring in the Ha Nam reach during 2021–2023 also continued to report poor water-quality conditions based on WQI (Giang et al., 2024), indicating that degradation remains a current management issue rather than only a historical condition.

At the same time, the scientific background for water-quality assessment in Vietnam is growing rapidly, as recent studies attempted to integrate the VN-WQI with PCA to identify priority indicators and polluted areas in central Vietnam and the Mekong Delta (Nguyen et al., 2026; Tong & Khang, 2026). The difference between the conducted studies and the study from the article lies in the fact that the previous ones used substantially denser temporal sampling than the present data set, allowing them to explore seasonal variability and better assess the seasonality of the water quality. The main purpose of the Nhue River analysis was to evaluate the general impact of the wastewater on the river by using a composite index instead of assessing the presence of specific pollutants. Thus, the composite water quality index can estimate the level of impairment for each station, while separate measurements can indicate the particular issue that might be a concern in a given area (Iqbal et al., 2019; Phuoc et al., 2026).

Thus, the goals of this work were to (i) determine the pollution gradient on the basis of the 12 sampling stations, (ii) describe, for the first time, characteristics of the DS and RS snapshots with a note that they cannot be extrapolated to the entire period, (iii) identify co-variation patterns among organic matter, nutrients, suspended matter, ions, and phylogenetic groups by applying correlation analysis and a PCA, (iv) identify station groups with similar tendencies in the results of the two campaigns using a HCA, and (v) demonstrate the value of the selected parameters and multivariate approaches in the context of the VN-WQI for pollution control at specific reaches. Since the present water quality dataset was not large enough for analyzing the seasonal variation of metals, they were used as additional indicators.

2. Materials and Methods

2.1 Study area and sampling design

The Nhue River is a tributary of the Red River originating from the Lien Mac Sluice in Hanoi city. It is fed by the Red River through the Lien Mac Sluice and flows into the Day River in Ha Nam province. The river is about 74 km long and has a drainage basin of about 1,100 km² (Le Phu Tuan et al., 2019). Some of the river uses include: receiving urban discharge, domestic waste, craft-village wastes, small-scale industrial effluents, and agricultural runoffs, besides providing irrigation and drainage services. It is a typical urban river of northern Vietnam receiving multiple forms of waste discharges.

Water samples were collected at 12 stations (R1–R12) along the river (Fig. 1) during one dry-season (DS) and one rainy-season (RS) campaign. The stations span the river from the Lien Mac Sluice to the lower reach near Phu Van and were selected to capture the longitudinal transition from Red River-influenced water through the densely urbanized and wastewater-impacted central reach to the lower river. The design was intended primarily to characterize spatial variability along the river. The two campaigns provide seasonal snapshots rather than replicated seasonal time series; therefore, DS–RS contrasts are interpreted descriptively and are not used for formal seasonal inference.

2.2 Analytical methods and quality assurance

Water-quality measurements included pH, dissolved oxygen (DO), electrical conductivity (EC), water temperature, biochemical oxygen demand (BOD₅), total suspended solids (TSS), ammonium (NH₄⁺), nitrate (NO₃⁻), phosphate (PO₄³⁻), total coliforms, and the measured metals As, Cd, Pb, Zn, and Cu. DO, pH, EC, and temperature were measured in situ using a portable multiparameter meter Hatch HQ40D. BOD₅ was determined according to ISO 5815-1:2019 using the 5-day method. TSS was determined gravimetrically after filtration through pre-weighed filters followed by drying at 103–105°C. NH₄⁺, NO₃⁻, and PO₄³⁻ were determined colorimetrically using a Hach DR900 spectrophotometer. Total coliforms were enumerated using the dry-rehydratable-film procedure recorded in the laboratory protocol as AOAC 991.14. Metals were measured by inductively coupled plasma mass spectrometry (ICP-MS). Because the available records do not document a dissolved-phase filtration step before ICP-MS analysis, the manuscript refers to these results as measured metal concentrations rather than dissolved-metal concentrations.

Quality-control procedures included calibration of field probes before measurement, analytical blanks and calibration standards for laboratory determinations, and duplicate checks where feasible. ICP-MS records included multi-point calibration and instrument-blank subtraction. The available dataset does not contain recovery, certified-reference-material, or method-detection-limit information for the metal analyses; accordingly, the metals were not used for risk calculations and were treated as ancillary indicators in the multivariate interpretation. Hydrological variables such as discharge, rainfall intensity, and water residence time were not measured concurrently; dilution, runoff, and low-flow conditions are therefore discussed only as plausible explanations rather than demonstrated causal mechanisms.

2.3 Water quality assessment using VN-WQI

The VN-WQI values were given for each station and campaign in the source analysis worksheet and were interpreted according to Decision 1460/QĐ-TCMT (Vietnam Environment Administration, 2019). For each parameter group contributing to the calculation of the VN-WQI, the data set includes information on particular indicators. Namely, these are pH (group I), metals (As, Cd, Pb, Cu, Zn) (group III), variables associated with dissolved oxygen (DO), biochemical oxygen demand (BOD₅), ammonium, nitrate, and phosphate (group IV), and total coliforms (group V). According to Decision 1460/QĐ-TCMT, the following six categories can be used to classify water quality: 91–100 – very good, 76–90 – good, 51–75 – moderate, 26–50 – poor, 10–25 – heavily polluted, and 0–9 – very heavily polluted. VN-WQI has been considered as an aggregate indicator used to classify water quality; thus, it cannot replace the interpretation of each particular variable. According to the instructions, when comparing water bodies using VN-WQI, it is necessary to ensure that the same variables are used for all samples analyzed; therefore, for the current research, only R1–R12 were compared in two campaigns.

2.4 Statistical analyses

Analyses were organized according to the study design rather than hypothesis-testing procedures for formal seasonal comparisons. DS and RS data were summarized descriptively using medians, ranges, and station-specific longitudinal profiles. Each seasonal snapshot contains 12 station observations; no priori upstream/downstream grouping was imposed for inferential testing. Total coliforms were log₁₀-transformed for correlation and multivariate analyses. Cd, reported as < 0.0005 mg/L in all samples, was excluded from correlation and PCA because it contained no quantitative variation. Pearson correlations were calculated separately for the two seasonal snapshots (n = 12 stations each) and interpreted strictly as co-variation. To focus PCA on the dominant water-quality signal and avoid distortion by censored or ancillary metal variables, PCA was performed on eight core variables (DO, EC, BOD₅, TSS, NH₄⁺, NO₃⁻, PO₄³⁻, and log₁₀ total coliforms) across the 24 station-season observations after z-score standardization. For HCA, the standardized DS and RS profiles of the same eight variables were concatenated for each station so that the two seasonal observations contributed equally to between-station comparisons; the 12 station profiles were then clustered using Ward's linkage and Euclidean distance. Statistical analyses and figure preparation were performed in Python using pandas, NumPy, SciPy, scikit-learn, and Matplotlib. These analyses were used for pattern recognition and station grouping, not for causal source apportionment or formal seasonal inference.

3. Results and Discussion

3.1 Physicochemical status and seasonal snapshots

Longitudinal station profiles (Fig. 2) show that pollution along the Nhue River does not follow a simple monotonic spatial gradient. The strongest combined deterioration occurred within the central wastewater-impacted reach, particularly across R2–R7, followed by partial recovery toward R8–R12. In the DS snapshot, DO was lowest within the R2–R7 reach, while BOD₅, TSS, NH₄⁺, and PO₄³⁻ were generally elevated there; from R8 onward, BOD₅ and TSS declined and DO increased toward R11–R12.

This pattern is consistent with the cumulative wastewater pressure previously reported for the Hanoi reach of the Nhue River (Hanh et al., 2010; Hue & Thanh, 2020; Trinh Anh et al., 2006). Importantly, the spatial interpretation here is based on station-by-station longitudinal profiles and the subsequent multivariate grouping, rather than on a pre-defined upstream-versus-downstream comparison.

The extent of water pollution was also severe in a regulatory/regional context. For instance, based on the entire course of the river, BOD₅ varied between 14.0 and 82.2 mg/L, implying that even the best water quality section did not meet the Class C standard (10 mg/L) of QCVN 08:2023/BTNMT; hence, all the samples fell under the worst category (Class D) in terms of BOD₅. Similarly, DO ranged between 1.04 and 3.60 mg/L, signifying extremely low levels of this parameter. Recently, such water quality trends were also observed in the heavily polluted urban canals in Ho Chi Minh City after untreated sewage effluents were discharged into the waterbodies, leading to decreased DO levels alongside increased concentrations of organic matter and ammonium and consequent low VN-WQI values (Dao et al., 2026). Thus, it can be concluded that Nhue River is a highly polluted watercourse with respect to domestic wastewater; consequently, the research questions related to the water quality of this river should focus on its spatial variability.

The two campaign snapshots differed in their overall concentration distributions (Fig. 3). Median EC decreased from 770 to 412.5 $\mu\text{S}/\text{cm}$, BOD₅ from 42.7 to 19.5 mg/L, and NH_4^+ from 23.0 to 10.0 mg/L, whereas median DO increased from 1.76 to 2.65 mg/L from DS to RS. Each boxplot in Fig. 3 summarizes the 12 station-specific observations within one campaign; no station-averaged water-quality value is used. These DS–RS contrasts are descriptive only because each season was sampled once. A larger wet-season flow may plausibly contribute to lower EC and several dissolved wastewater indicators through dilution. Similar wet-season improvement has been reported in heavily urbanized tropical catchments affected by domestic sewage (Dao et al., 2026), although enhanced runoff and wash-load transport can produce the opposite response for some constituents (Abdullah et al., 2025; Phuoc et al., 2026). Thus, hydrological variability is a plausible contextual driver of the observed campaign differences, but it cannot be tested directly with the present dataset. Despite these overall differences, the R2–R7 high-pressure reach remained distinct in both campaigns, indicating a persistent spatial structure.

3.2 Nutrients and microbial indicators

The organic, nutrient, suspended-solid, and microbial indicators did not show a consistent pattern in the river. For instance, there was a high concentration of NH_4^+ , and PO_4^{3-} in most of the upstream and midstream stations. In contrast, BOD₅ and TSS reached their maximum levels at station R2-R7.

Moreover, there was a high level of total coliform bacteria in both the DS ($4.0 \times 10^3 - 1.87 \times 10^5$ CFU/100 mL) and RS ($7.0 \times 10^3 - 1.65 \times 10^5$ CFU/100 mL) stations during the two campaigns. This observation is critical since the chemical indicators improved in the RS snapshot compared to total coliform bacteria. In other words, there was an apparent recovery in oxygen levels and nutrient in some stations. However, this could not be reflected by the degree of microbial pollution.

The simultaneous occurrence of BOD₅, NH₄⁺, and PO₄³⁻, TSS, and coliforms suggests a pollution source of wastewater origin. Degradable organic matter will contribute to increased oxygen consumption; in the presence of nitrifying bacteria, ammonium can also contribute to oxygen consumption; phosphate is typically enriched in domestic wastes and detergents; increased microbial counts are an indicator of potential fecal contamination; and suspended matter can provide a habitat for microbes. It is the combination of these factors that makes the results of interest. Recent studies carried out in Vietnam also emphasize the importance of BOD₅, ammonium, microbial markers, and suspended matter in polluted surface-water bodies (Phuoc et al., 2026; Tong Nguyen Xuan & Khang Luu Tang Phuc, 2025), while the 2026 assessment of Ho Chi Minh City canals reported severe organic–nutrient–microbial contamination under intense urban wastewater pressure (Dao et al., 2026).

In addition, it is important to note that co-variation is not source apportionment; domestic sewage may well dominate in the context of the Nhu riverine system and the microbial source-tracking evidence previously reported (Mai Tanaka et al., 2018). Nevertheless, the relative impact of crafts village, industrial, agricultural, and urban inputs appears to vary with site, and total coliform bacteria are a generic indicator of sanitary risk, not a specific source. Further investigations of this reach should include the analysis for *Escherichia coli* or fecal coliform bacteria, if possible, microbial source-tracking markers, and a survey of inputs (discharge estimates and outfall locations) to test the hypothesis that similar patterns of total coliform bacteria are related to load and source dynamics at this particular site.

3.3 Supplementary behavior of measured metals

Measured As, Pb, Zn, and Cu contents showed a certain station-to-station variability, which was less pronounced than that of the core organic-nutrient-microbial indicators (Fig. 4). Cd was below 0.0005 mg/L in all stations, and this value was excluded from consideration by converting it into an artificial numerical code instead of using a value of 0. Pb and Zn contents demonstrated local maxima, while those of As and Cu varied within a narrow range. These observations indicate that the water column metal content exhibits weaker spatial structure than the core indicators; therefore, they represent a subordinate secondary pollution pattern.

The fact that there was not a significant water-column signal does not necessarily mean that metals were not important in the Nhue-Day basin. Ngo et al. (2021) report considerable accumulations of Zn, Cu, Pb, and Cd both in sediments and biota and argue that metal inputs can be accumulated in sediments in much higher concentrations than a single water sample can represent. Metals can be found in dissolved, particulate, and sedimentary phases and can be redeposited from one phase to another depending on the physiochemical environment, notably pH, Eh, oxygen, and organic matter. Therefore, what the present water-column findings suggest is, instead, the difference between the instantaneous multivariate signal represented by the water column and the integrated signal reflected in the two campaigns' findings. Organic-nutrient-microbial pollution is evident in both; however, metal risk is probably better assessed in a partitioning-specific manner and through time-integrated matrices than the short-term water column.

For this reason, the present paper does not attempt to rank metals by risk or to compare their concentrations with established health criteria. Such an analysis would require additional information on the degree of removal in the treatment plants, determination of detection limits and recovery rates for each metal, and a design that relates water with suspended matter and biota. Monitoring trace elements near industrial enterprises and craft villages is undoubtedly necessary; however, it should be regarded as a separate issue, the solution of which goes beyond the scope of the current PCA.

3.4 Correlation structure, principal components, and station clustering

Pearson correlations calculated from the station data supported the broader co-variation pattern identified by the longitudinal profiles and multivariate analyses. In DS, BOD₅ correlated with TSS ($r = 0.86$) and log₁₀ total coliforms ($r = 0.72$), TSS correlated with log₁₀ total coliforms ($r = 0.78$), and NH₄⁺ and PO₄³⁻ were strongly interrelated ($r = 0.89$); both nutrients were associated with lower DO, with NH₄⁺ showing $r = -0.84$ with DO. In RS, NH₄⁺–PO₄³⁻ ($r = 0.96$) and TSS–log₁₀ total coliforms ($r = 0.90$) remained strongly related, while EC was positively associated with NH₄⁺ and PO₄³⁻. Because each seasonal matrix contains only 12 stations, individual coefficients are interpreted cautiously as exploratory evidence of co-variation rather than mechanistic proof.

This pattern supports the interpretation that an associated wastewater gradient underlies these observations. The BOD₅-TSS-coliform trend reflects interactions among organic matter, suspended particles, and fecal indicator bacteria, whereas the concurrent variation in ammonium and phosphate concentrations represents associations between two nutrients typical of wastewater sources (Fig. 2). A similar explanation applies to the observed negative correlation between DO and ammonium, with depleted dissolved oxygen associated with hypoxic conditions conducive to nitrogenous waste production and accumulation. It is challenging to distinguish between nitrification and organic matter remineralization processes responsible for this pattern using the data at hand. The same trends have been reported for the Nhue River, Vietnam (Hue & Thanh, 2020), and recently emerged in analyses of organic, nitrogen, solids, and microbial variables in Vietnamese rivers that jointly explained a large fraction of variance in water quality (Phuoc et al., 2026; Tong Nguyen Xuan & Khang Luu Tang Phuc, 2025).

Given the small seasonal sample size, correlation matrices are treated as exploratory secondary evidence (Supplementary). Their value lies in the recurrence of the same pattern across independent analytical views—longitudinal profiles, PCA loadings, and HCA grouping—rather than in any single correlation coefficient. This convergence provides stronger support for the existence of a coherent pollution gradient while avoiding mechanistic or source-attribution claims.

The PCA of the eight core variables revealed a compact and environmentally interpretable structure (Fig. 5). PC1 explained 62.0% of standardized variance and was primarily associated with contrasting patterns of DO against BOD₅, TSS, NH₄⁺, PO₄³⁻, EC, and log₁₀ total coliforms. Rather than assigning a

specific causal mechanism to this axis, it is interpreted as a broad transition from relatively oxygenated water to water enriched in organic matter, nutrients, suspended solids, ionic constituents, and microbial indicators. The large proportion of variance captured by PC1 indicates that these core variables responded coherently to the dominant degradation pattern along the river. A recent study in central Vietnam likewise identified BOD₅, ammonium, microbial indicators, and turbidity as major contributors to PCA structure, although the overall pollution level there was lower than in the Nhue River (Phuoc et al., 2026).

PC2 accounted for 17.2% of variance and was primarily shaped by the combined effects of NO₃ – and EC, suggesting the presence of a secondary pattern, which was not masked by the strong influence of PC1. This could be explained by the fact that nitrates participate in a different balance of oxidation-reduction processes, runoffs, and inputs from upstream compared to ammonium. Thus, DS and RS are partially separated by ordination, but this should not be overinterpreted as proof of seasonal separation. Together, PC1 and PC2 account for 79.2% of variance, which emphasizes the importance of dimensionality reduction in this dataset while also illustrating that the main source of pollution cannot be reliably distinguished on the plot.

HCA offers an independent spatial cross-validation of this interpretation. With two-campaign standardized profiles, the best grouping again separated R2 – R7 from the stations located outside the highest pressure zones while bringing together R1/R8 and low groups into transitional and low reach classes respectively. The agreement with the longitudinal pattern is critical for management because the clustering is not a priori selection of upstream, mid, and downstream reaches as often used in water quality assessments. The similarity across the sites emerged out of multivariate analysis during both campaigns. The management practice in Vietnamese rivers also used a comparable two-step procedure to group similar stations based on their monitoring characteristics before exploring the relationships within the group using statistical analysis (Hue & Thanh, 2020; Tong Nguyen Xuan & Khang Luu Tang Phuc, 2025). Therefore, the most appropriate management implication would be a differential surveillance and control of the identified groups rather than claiming that they represent specific hydromorphological river typologies.

3.5 Water quality assessment using VN-WQI

The VN-WQI was low throughout the river (Fig. 7). Under the six-class scheme of Decision 1460/QĐ-TCMT, the DS snapshot included two stations with VN-WQI < 10 (very heavily polluted), nine stations with VN-WQI 10–25 (heavily polluted), and only R12 in the poor class (VN-WQI = 26). In the RS snapshot, R1–R11 were heavily polluted (VN-WQI 14–25), whereas R12 remained poor (VN-WQI = 45). Thus, even R1, with VN-WQI values of 24 (DS) and 25 (RS), cannot be treated as a clean-water reference. Overall, VN-WQI indicates basin-wide impairment, while the station-specific profiles and multivariate analyses provide greater spatial resolution for identifying the most strongly affected reach. Compared with recent assessments of the Huong River–Tam Giang system, where most samples were rated moderate to

excellent (Phuoc et al., 2026), the Nhue River showed substantially poorer overall status and was more comparable to heavily polluted urban canals in Ho Chi Minh City (Dao et al., 2026).

Comparison of VN-WQI with the longitudinal parameter profiles provides complementary information. VN-WQI summarizes multiple indicators into a single value suitable for overall classification and communication, but it can obscure which variables and reaches drive impairment. The station profiles, PCA, and HCA consistently identify R2–R7 as the principal reach of combined organic, nutrient, suspended-solid, and microbial pressure. Accordingly, VN-WQI is most useful here as a basin-wide status indicator, whereas the parameter-specific and multivariate analyses are needed to locate pollution foci and management priorities (Iqbal et al., 2019; Phuoc et al., 2026).

For managers, the obtained results allow for the formulation of a priority-based response. Thus, priority should be given to the group of stations R2 – R7 for which wastewater interception measures, inventory of outfalls, and intensified monitoring of organic, nutrient, and microbial status are required. This concern is dictated by the fact that these stations demonstrate the greatest concentrations of priority pollutants and their combined grouping. For the group R8 – R11, monitoring should also be carried out since the recovery of chemical indicators is partial, while overall WQI remains close to moderate and microbial pollution is still significant. The station R12 can be used as a reference or affected one to study the recovery process downstream rather than a control station. Finally, at the basin scale, future monitoring should shift from monitoring of concentration to load with the implementation of water chemistry analyses, discharge measurements, and rainfall observations. Furthermore, it is necessary to include microbial tracking and water metal composition analyses for each period.

3.6 Study limitations and implications

The primary limitation is temporal replication: one campaign per season precludes any assessment of inter-annual or intra-seasonal variability, and thus the DS–RS contrasts should be viewed descriptively only. The lack of concurrent measurements of discharge, rainfall, travel-time, and wastewater-load prevented an attempt to separate the processes affecting the dilution, reaeration, self-purification, and time-varying sources. Nevertheless, these limitations are mostly related to the design of the study and do not undermine the finding of the spatial patterns presented, which were consistently observed across different analytical approaches applied to the same set of stations.

Analytical limitations also dictate interpretation; total coliforms are an indicator of general waterborne microorganism but do not specify fecal origin; future work should consider measuring *E. coli*, fecal indicators, or microbial source-tracking markers. Nutrients were reported using the units of measure as retained in the original laboratory database; therefore, comparisons of nitrogen or phosphorus equivalents should be attempted only when explicitly noting the analytical reporting basis. For metals, the data record does not include sufficient phase-specific information on sample filtration to allow definitive interpretation of potential ecological risk; a full suite of recovery information, analyses of certified reference materials, and method detection limits would be necessary to fully evaluate metal

data in the context of environmental risk. The metals data are therefore most appropriately treated as an ancillary set of water column indicators.

Within these constraints, the study provides a management-relevant baseline for designing enhanced monitoring. Future surveys should repeatedly sample the R2–R7 hotspot together with stations immediately above and below this reach, while adding concurrent flow, rainfall, outfall, *E. coli* or source-tracking measurements, and sediment/particulate metal analyses. Such a design would allow the mechanisms underlying the present spatial patterns to be tested directly. The principal value of the current study therefore lies not only in documenting spatial patterns, but also in identifying where additional monitoring and management effort is most likely to be informative.

4. Conclusions

Pollution in the Nhue River did not follow a simple monotonic longitudinal gradient. The R2–R7 reach showed the strongest combined organic, nutrient, suspended-solid, and microbial pressure in both campaign snapshots, followed by partial recovery toward the lower stations. Severe impairment was evident throughout the river, with BOD₅ ranging from 14.0 to 82.2 mg/L. According to VN-WQI, the DS snapshot contained two very heavily polluted stations (< 10), nine heavily polluted stations (10–25), and one poor station (R12); in the RS snapshot, all stations except R12 were heavily polluted and R12 was poor. Differences in median DO, EC, BOD₅, and NH₄⁺ between DS and RS are descriptive only because each season was sampled once and concurrent hydrological measurements were unavailable.

PCA, correlation analysis, and HCA identified the same organic-nutrient-microbial cluster. PC1 alone accounted for 62% of the variance, while PC1-PC2 – for 79.2% of standardized data, and HCA highlighted R2-R7 reach as a separate group. VN-WQI demonstrated the overall basin impairment status but revealed less information about the most polluted reach. Metals need to be assessed at the water column scale for each season with QA/QC to define risks. The most plausible management scenario includes improving the wastewater treatment and spatial inventory of point sources in the R2-R7 reach, monitoring microbes downstream, and designing future monitoring efforts around seasonal surveys with load calculations, source apportionment, and metal partitioning.

Declarations

Ethics approval

Not applicable. The study involved environmental surface-water sampling only and did not involve human participants or animals.

Competing interests

The authors declare no competing interests.

Funding

The authors did not receive support from any organization for the submitted work.

Author Contribution

Pham Duy Dong was primarily responsible for sample collection, laboratory analysis, and manuscript preparation. Nguyen Sy Toan was responsible for data analysis and manuscript revision. Nguyen Thanh Gia was responsible for manuscript revision. Nguyen Thi Hue was responsible for metal analysis and manuscript revision. Watanabe Toru was responsible for planning the water sampling and manuscript revision.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

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Figures

Fig. 1

Map of sampling points along the Nhue River

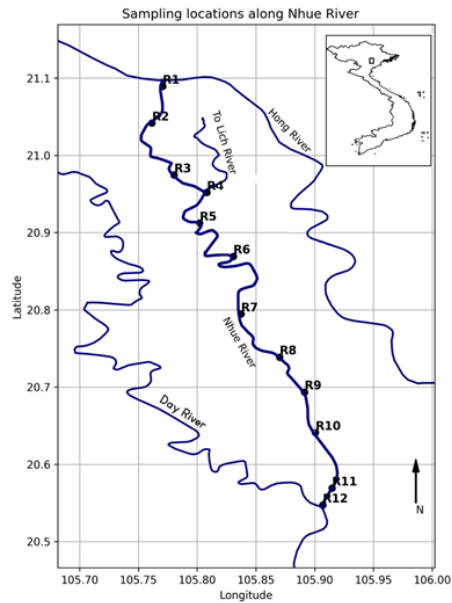


Fig. 1 | Nhue River manuscript

Figure 1

See image above for figure legend

Fig. 2

Longitudinal profiles of core water-quality indicators at R1–R12 during the dry-season (DS) and rainy-season (RS) sampling campaigns

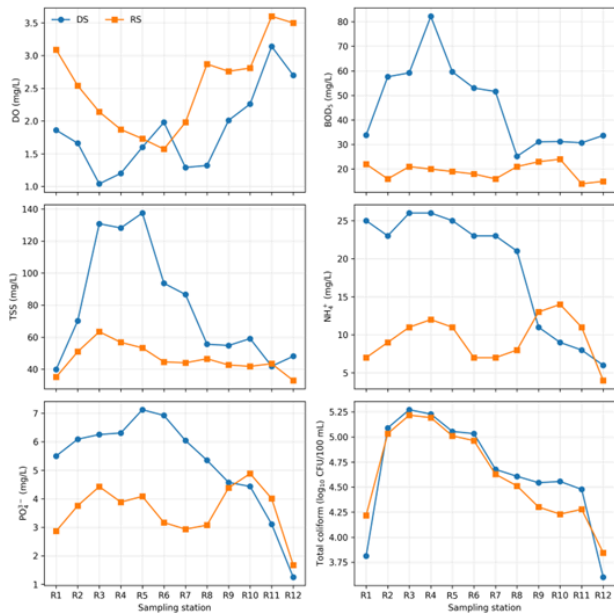


Fig. 2 | Nhue River manuscript

Figure 2

See image above for figure legend

Fig. 3

Distributional comparison of selected water-quality indicators between the two seasonal snapshots. Each boxplot summarizes the 12 station-specific observations for one campaign; no station-averaged value is used. The comparison is descriptive and no population-level seasonal inference is made

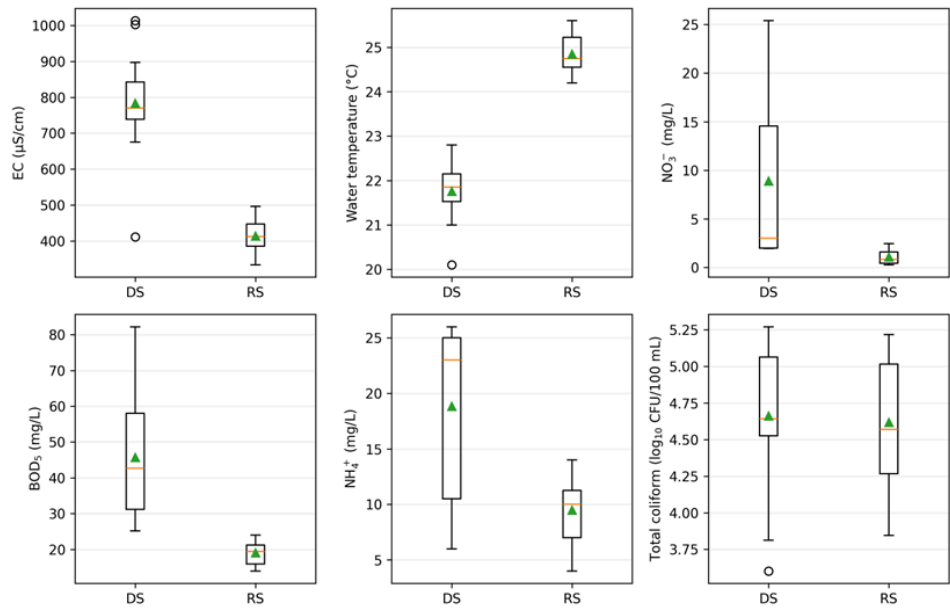


Fig. 3 | Nhue River manuscript

Figure 3

See image above for figure legend

Fig. 4

Spatial variation of measured As, Pb, Zn, and Cu concentrations along the Nhue River. Cd is not shown because all results were reported as <0.0005 mg/L

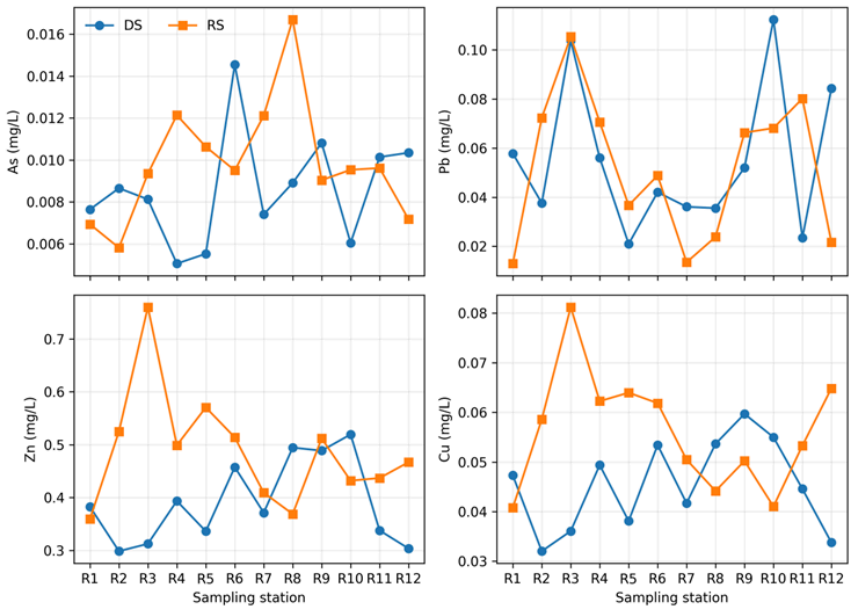


Fig. 4 | Nhue River manuscript

Figure 4

See image above for figure legend

Fig. 5

PCA biplot of eight standardized core water-quality variables across 24 station-season observations. PC1 and PC2 explain 62.0% and 17.2% of total variance, respectively. Total coliforms were log₁₀-transformed

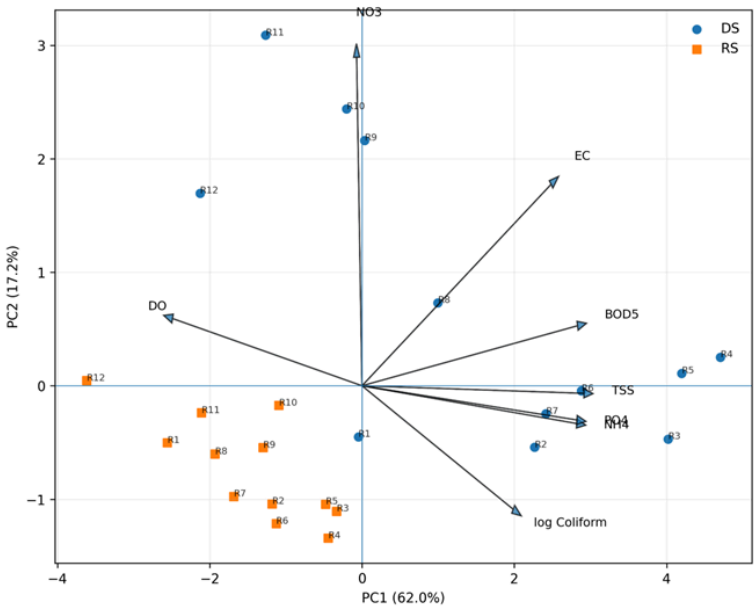


Fig. 5 | Nhue River manuscript

Figure 5

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Fig. 6

Hierarchical clustering of R1–R12 using Ward’s linkage and Euclidean distance on station profiles that concatenate standardized DS and RS values of the eight core water-quality variables

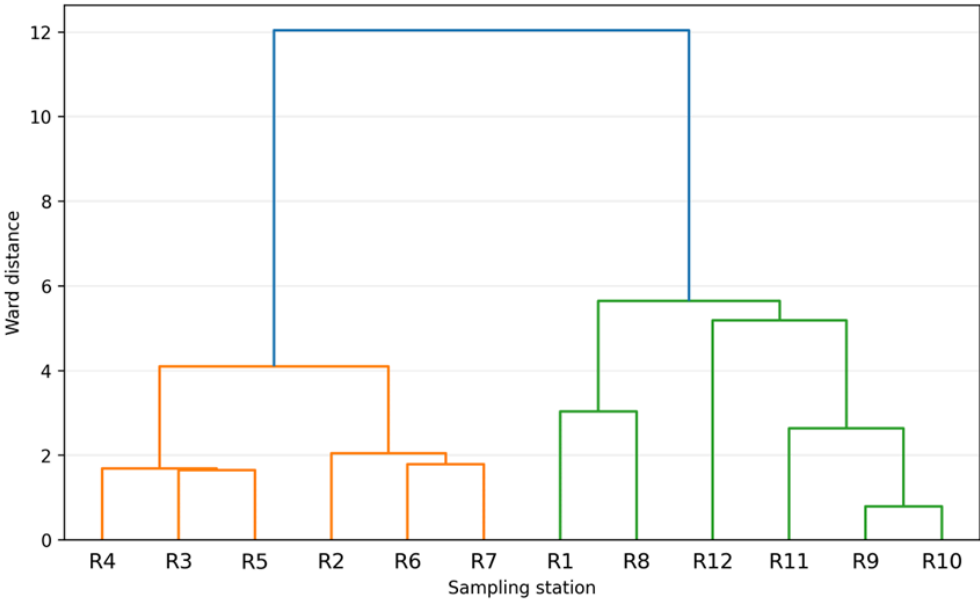


Fig. 6 | Nhue River manuscript

Figure 6

See image above for figure legend

Fig. 7

VN-WQI at R1–R12 for the two seasonal snapshots. Dashed lines mark the principal class boundaries relevant to these data under Decision 1460/QĐ-TCMT: <10, very heavily polluted; 10–25, heavily polluted; and 26–50, poor

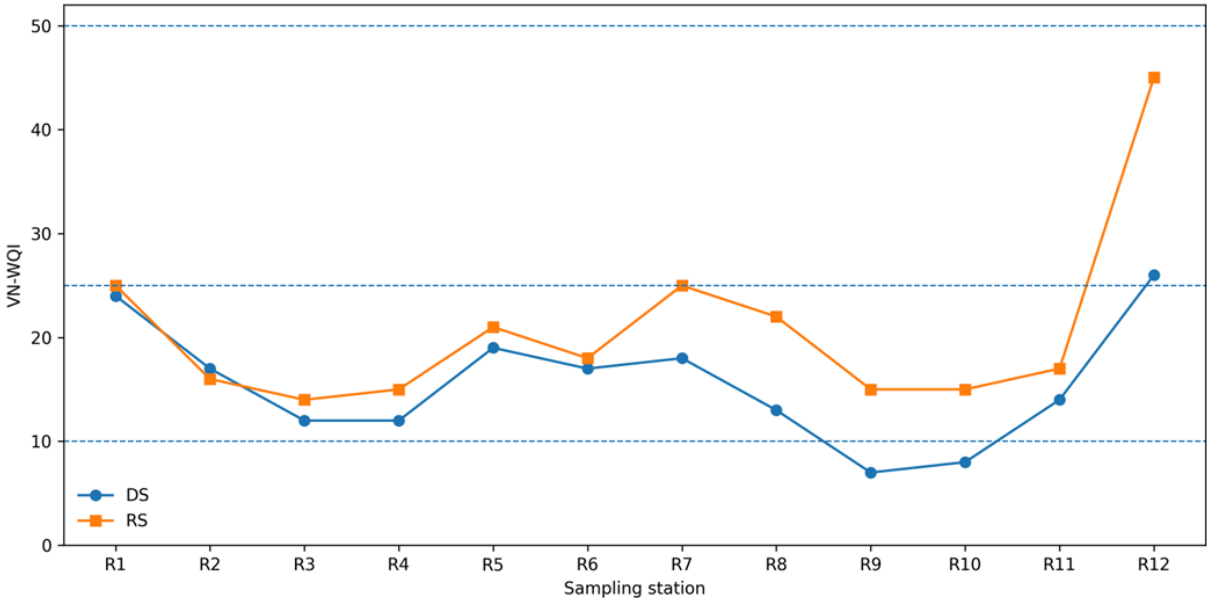


Fig. 7 | Nhue River manuscript

Figure 7

See image above for figure legend

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