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Original Article

Seasonal and Interannual Variability of Water Quality in Bien Ho, Central Highlands of Vietnam: Insights from Continous Monitoring and Multivariate Statistical Analysis

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Abstract This study assessed temporal variability in the water quality of Bien Ho, a strategic volcanic freshwater lake in the Central Highlands of Vietnam, using continuous monitoring data collected during 2020-2024. Nine physicochemical parameters were analyzed, including temperature, pH, dissolved oxygen (DO), chemical oxygen demand (COD), total suspended solids (TSS), turbidity, ammonium (NH_4^+), dissolved iron (Fe), and dissolved manganese (Mn). Descriptive statistics, Spearman correlation, ANOVA/MANOVA, and Principal Component Analysis (PCA) were applied to evaluate seasonal and interannual variability and to identify dominant multivariate patterns. Most parameters remained within the limits of QCVN 08:2023/BTNMT (Column A), indicating generally favorable water quality for domestic water supply after appropriate treatment. However, clear temporal variability was observed, particularly for turbidity, TSS, DO, Fe, and Mn. Statistical tests confirmed significant effects of year, season, and their interaction on the water quality dataset. Spearman correlation showed a strong positive relationship between COD and TSS, while pH was positively associated with DO and temperature. PCA extracted two principal components explaining 49.8% of the total variance. The first component represented a hydro-physical and oxygenation gradient associated with temperature, DO, pH, turbidity, and Fe, whereas the second reflected a particulate-organic and redox-sensitive gradient dominated by TSS, COD, and Mn. The increased variability observed during 2022-2024

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indicates the need for sustained high-frequency monitoring, particularly in relation to monsoon hydrology and hydrological disturbances.

Keywords: water quality; continuous monitoring; seasonal variability; interannual variability; multivariate statistical analys

1. Introduction

Water resources in the Central Highlands of Vietnam are increasingly effected by seasonal drought, declining groundwater availability, land-use change, urban expansion, agricultural activities, and tourism development. These pressures are particularly important for strategic freshwater bodies that support domestic water supply and regional socio-economic development [1, 2-4]. Bien Ho, also known as T'Nưng Lake, is a natural volcanic freshwater lake formed ~200,000 years ago, located on the Pleiku basalt plateau in Gia Lai Province [5]. The lake with a storage capacity of about 23 million m^3 is an important domestic water source for Pleiku City (former boundary) and has significant ecological, landscape, and tourism value [1, 5].

Despite its importance, Bien Ho is exposed to increasing hydrological and anthropogenic pressures from infrastructure construction, agricultural runoff, domestic wastewater discharge, tourism activities, and groundwater abstraction within the catchment. In addition, the breach of the regulating dam separating a nearby irrigation reservoir from Bien Ho on 29 September 2022 allowed irrigation water to overflow into the lake, potentially modifying its hydrological regime and short-term water quality dynamics. These conditions highlight the need for a systematic assessment of temporal water quality variability in the lake.

Lake water quality is controlled by complex interactions among physical, chemical, biological, hydrological, and catchment-related processes [6, 7]. Because individual water quality parameters are often interdependent, conventional univariate assessment may be insufficient to identify the dominant mechanisms controlling water quality variability [6-9]. Multivariate statistical methods, particularly Principal Component Analysis (PCA), provide an effective approach for reducing data dimensionality, identifying relationships among variables, and distinguishing the major hydrochemical gradients in complex water quality datasets [8-22].

Previous studies on Bien Ho and freshwater systems in the Central Highlands have provided useful information on water balance, phytoplankton-environment relationships, rainfall variability, and catchment erosion processes [2-4, 23]. However, most available studies were based on short-term or periodic observations and have not adequately captured seasonal and interannual variability under the combined influences of monsoon climate, catchment processes, anthropogenic pressures anthropogenic pressure, and hydrological disturbance. Therefore, long-term monitoring data are necessary to clarify the temporal structure and controlling factors of water quality in Bien Ho.

This study applies multivariate statistical analysis, with emphasize on PCA, to evaluate water quality variability in Bien Ho during 2020-2024 using a set of physicochemical parameters (temperature, pH, dissolved oxygen, chemical oxygen demand, total suspended solids, turbidity, ammonium, iron, and manganese). The study addresses to: (i) characterize seasonal and interannual variations in water quality parameters; (ii) identify the groups of parameters explain the dominant temporal patterns of water quality variability. The working hypothesis is that water quality variability in Bien Ho is mainly governed by two interacting mechanisms: seasonal hydrological forcing, which enhances runoff, turbidity, and suspended-solid inputs during the rainy season; and internal lake processes, including oxygenation, sediment-water interaction, and redox-sensitive metal mobilization, which become more evident during periods of lower water exchange. The results are expected to provide a scientific basis for long-term monitoring, early warning, and sustainable management of this strategic volcanic lake.

2. Study Area, Data Sources, and Research Methods

2.1. Study Area

The study was conducted at Bien Ho Lake, located in Bien Ho Commune, approximately 7 km northwest of Pleiku City center (former administrative boundary), Gia Lai Province, on the Pleiku basalt plateau in the Central Highlands of Vietnam (Fig. 1). The monitoring site is situated within the main lake basin, which is surrounded by gently undulating basaltic terrain and well-developed red basalt soils. The adjacent catchment includes forested land, agricultural areas, residential zones, and tourism-related infrastructure, all of which may influence runoff generation, suspended-sediment transport, and nutrient input during rainfall events [1, 4].

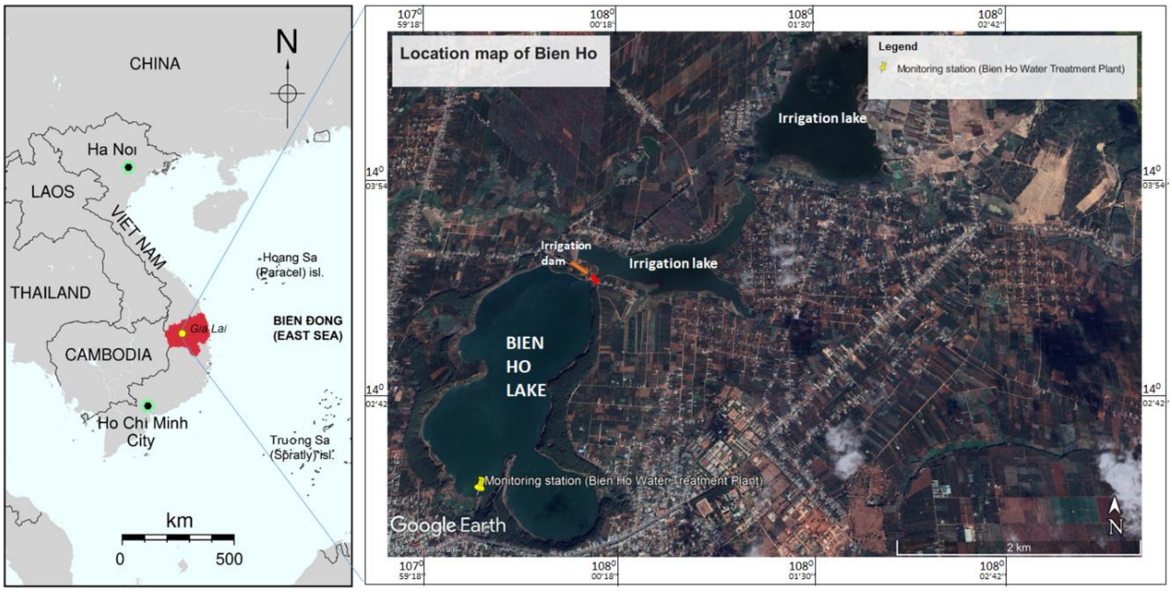

Figure 1. Location of Bien Ho Lake and the automatic water quality monitoring station in Bien Ho commune, Gia Lai Province.

The area is characterized by a tropical monsoon climate with two distinct seasons. The rainy season generally extends from May to October and contributes approximately 85-95% of annual rainfall, whereas the dry season lasts from November to April and is marked by low precipitation and high evaporation (Fig. 2) [1-2]. This seasonal contrast is a major control on lake hydrology, affecting water level, residence time, runoff intensity, sediment input, and water-column mixing. During the rainy season, rainfall-driven runoff may increase turbidity, total suspended solids, and catchment-derived material inputs. In contrast, dry season conditions may promote longer water residence time, sedimentation, and internal biogeochemical processes [1, 3].

Bien Ho has no large permanent inflowing streams and receives water mainly from direct rainfall, catchment runoff, and seasonal exchange with the surrounding basalt aquifer [3]. The lake is separated from a nearby irrigation reservoir by a regulating dam. On 29 September 2022, this dam was breached, allowing irrigation water to overflow into the lake. This event represents an important hydrological disturbance that may have affected short-term water quality dynamics, particularly through changes in suspended matter, turbidity, and catchment-derived inputs. These characteristics make the site suitable for assessing seasonal and interannual variability in water quality under the combined influence of monsoon hydrology, basaltic catchment processes, and hydrological disturbance.

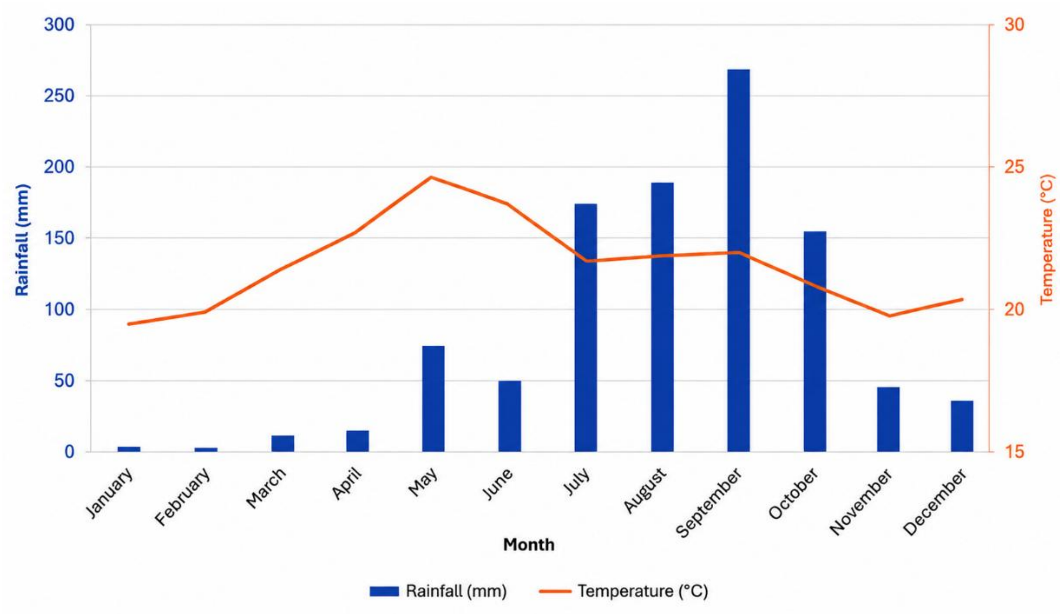

Figure 2. Monthly variation of rainfall and temperature at the Bien Ho automatic monitoring station in 2025.
Source: Data collected from the automatic monitoring station installed by the authors.

2.2. Data Sources and Quality Control

This study used continuous water quality monitoring data collected from the automatic monitoring station at Bien Ho during 2020-2024. Nine physicochemical parameters were analyzed, including temperature, pH, dissolved oxygen (DO), chemical oxygen demand (COD), total suspended solids (TSS), turbidity, ammonium (NH_4^+), dissolved iron (Fe), and dissolved manganese (Mn). The dataset was recorded at hourly intervals and aggregated into daily values to reduce short-term instrumental noise and provide a consistent temporal resolution for statistical analysis.

The monitoring parameters, instruments, measurement principles, and analytical characteristics are summarized in Table 1. Direct sensor measurements were used for pH, DO, NH_4^+, and turbidity, whereas Fe and Mn were determined using an automated spectrophotometric analyzer. COD and TSS were derived from optical sensor signals and were therefore treated as sensor-based estimates. These parameters require regular calibration and verification against laboratory measurements to ensure data reliability [6, 8, 9].

Before statistical analysis, the raw dataset was screened to remove invalid records associated with sensor malfunction, calibration and maintenance periods, data transmission errors, and physically unrealistic values. Missing or invalid hourly records were excluded before daily aggregation. Because the dataset was obtained from a single automatic monitoring station, the analysis represents temporal variability at the monitoring location rather than spatial variability across the entire lake.

Table 1. Summary of monitoring data, instruments, and measurement principles

Parameter	Instrument model	Accuracy (repeatability/ linearity)	Measurement method/ principle
Temperature	HP-200	Accuracy (repeatability): ±0.3ºC	Pt1000 temperature sensor
pH		Accuracy (repeatability): ±0.03 pH units	Glass electrode method with automatic temperature compensation (ATC).
Ammonia Nitrogen (NH_4^+)	HC-200NH (AM-2000 Sensor)	Repeatability: 3% ±1 digit or 0.2 mg/L ±1 digit (whichever is larger).	Ion-selective electrode (ISE) method using liquid membrane with K+ ion compensation.
COD (optical-derived)	OPSA-150	Repeatability and linearity: Within ±2.0% full scale (for range 0.1-2.5 Abs).	Optical COD estimation based on dual-path, dual-wavelength UV–Vis absorbance measurement with rotary cell length modulation
Total suspended Solids (TSS)	HU-200TB-IM (SS-150 Optical Sensor)	Repeatability: Within ±2% of reading or ±0.5 mg/L (for scattering/transmission).	Optical suspended solids measurement based on nephelometric light scattering at low concentrations and light transmission at concentrations >50 mg/L.
Turbidity		Repeatability: Within ±2% of reading or ±0.5 NTU (whichever is larger).	Nephelometric method based on 90° light scattering with transmission compensation.
Dissolved Oxygen (DO)	HC-200NH (DO-2000 Optical Sensor)	Repeatability: ±0.5% of range; Linearity: ±2.0% of range.	Optical dissolved oxygen measurement based on luminescence quenching.
Dissolved Fe and Mn	SEIBOLD COMPOSER	Precision: >97%; Error: ±3%.	Spectrophotometric determination based on the Beer–Lambert law using metal-chelate complex formation.

2.3. Statistical Analysis

Statistical analyses were performed to evaluate temporal variability and identify the main factors controlling water quality in Bien Ho. Descriptive statistics were first used to summarize the distribution of the nine water quality parameters and to examine seasonal and interannual patterns. Spearman correlation analysis was applied to assess monotonic relationships among variables because water quality datasets often show non-normal distributions and nonlinear associations [8, 14, 24].

Analysis of variance (ANOVA) was used to test whether individual water quality parameters differed significantly between years and seasons. When the combined response of multiple parameters was considered, multivariate analysis of variance (MANOVA) was applied to evaluate overall temporal differences in the water quality dataset [8, 25]. Statistical significance was assessed at $p < 0.05$.

PCA was applied to reduce data dimensionality and identify the dominant hydrochemical gradients controlling water quality variability. Prior to PCA, all variables were standardized using z-score transformation to remove the influence of different units and measurement scales [15, 26]. PCA was performed using a correlation matrix, which is appropriate for multivariate environmental datasets composed of variables with different units [9, 17]. The number of retained components was determined based on eigenvalues greater than 1, inspection of the scree plot, and the cumulative percentage of explained variance [9, 15].

To improve interpretability, retained components were rotated using orthogonal

Varimax rotation with Kaiser normalization. Variables with absolute factor loadings greater than 0.60 were considered to have a strong contribution to a principal component. The resulting component structure was interpreted in relation to hydrological, particulate, organic, oxygenation, and redox-related processes affecting lake water quality [16, 17, 21, 22, 27].

3. Results and Discussion

3.1. Temporal Variability of Water Quality

The monitoring data for 2020-2024 showed clear temporal variability in the physicochemical conditions of Bien Ho. Overall, most parameters remained within the limits specified in QCVN 08:2023/BTNMT (Column A), indicating that the lake generally maintained water quality suitable for domestic water supply after appropriate treatment [6]. However, marked seasonal and interannual fluctuations were observed for several parameters, particularly turbidity, TSS, DO, Fe, and Mn, suggesting that the lake system was sensitive to both seasonal hydrological variation and episodic disturbance.

Water temperature showed a distinct seasonal pattern (Fig. 3). Lower and more stable values were recorded during the dry season, generally ranging from approximately 23 to 27 °C, whereas higher values, often exceeding 27 °C, occurred during the rainy season. This pattern is consistent with the tropical monsoon climate of the Central Highlands, where seasonal changes in solar radiation, rainfall, and mixing conditions influence lake thermal regimes [1, 2]. Interannual variation also indicated relatively higher and more variable temperatures during 2020-2021, followed by lower and more stable conditions during 2023-2024 (Fig. 4).

The pH values ranged mainly from neutral to slightly alkaline conditions, approximately 7.0-8.6 (Fig. 3). Higher median pH values were generally observed during the dry season, while lower and more stable values occurred during the late rainy season and end of the year. These variations remained within the acceptable range for surface water quality and are consistent with previous observations in Bien Ho, where pH variability was associated with seasonal changes in biological activity and hydrological conditions [23].

Turbidity and TSS exhibited more variable behavior than pH and temperature. Turbidity fluctuated continuously throughout the year, while TSS generally remained low but showed occasional peaks (Fig. 3). Higher turbidity and episodic TSS increases were observed during the rainy season and transition periods from the dry to rainy season. These results are consistent with rainfall-driven runoff and suspended-particle transport from basaltic catchments, as previously noted for the Bien Ho area and other monsoon-influenced lake systems [1, 4, 22]. However, because this study did not directly quantify sediment load or runoff volume, these mechanisms should be interpreted as probable hydrological controls rather than directly measured processes.

NH_4^+ and COD concentrations remained generally low throughout the monitoring period (Fig. 3). NH_4^+ ranged approximately from 0.01 to 0.16 mg/L, while COD median values were mostly between 1 and 3 mg/L. These values indicate limited organic and ammonium pollution during most of the study period and are broadly consistent with previous observations that Bien Ho has relatively good water quality and low nutrient concentrations [1, 23]. Several short-term increases in COD and NH_4^+ were observed, but the available dataset does not allow direct identification of specific pollution sources.

DO concentrations generally exceeded 6 mg/L, indicating predominantly aerobic conditions in the monitored water column (Fig. 3). Higher DO values were observed during cooler months, whereas lower values and wider variability occurred during parts of the rainy season and in recent years, especially 2023-2024 (Fig. 4). These variations may reflect the combined influence of temperature, hydrological mixing, and organic matter input, but additional depth-profile and biological data would be required to confirm the controlling mechanisms.

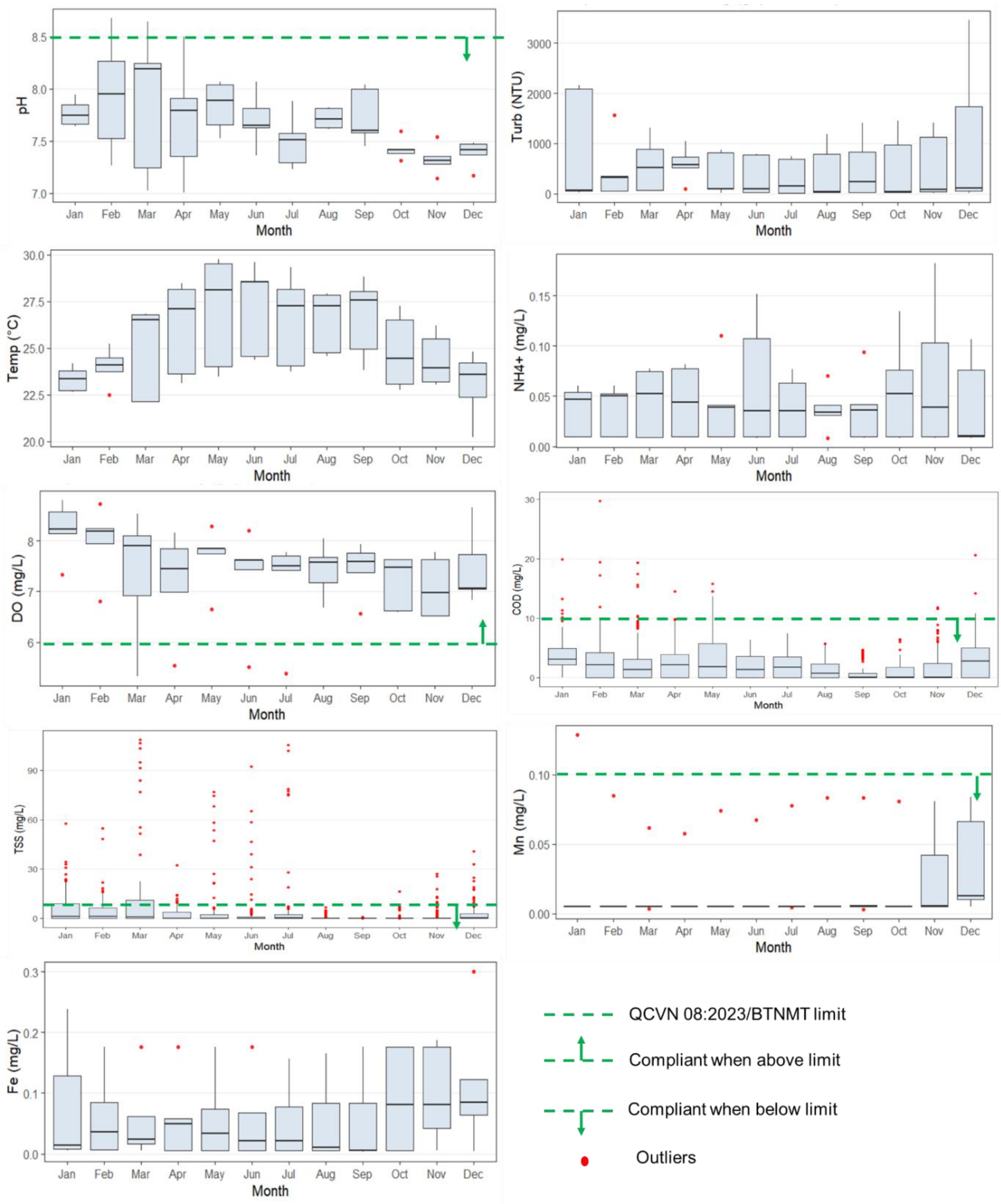

Figure 3. Monthly variability of physicochemical water quality parameters in Bien Ho during 2020-2024. Boxes show the interquartile range (IQR), center lines indicate medians, whiskers represent 1.5 × IQR, and red points denote outliers. Green dashed lines indicate the corresponding QCVN 08:2023/BTNMT limits, with arrows denoting the direction of compliance. Parameters without threshold lines complied with the applicable standards throughout the monitoring period.

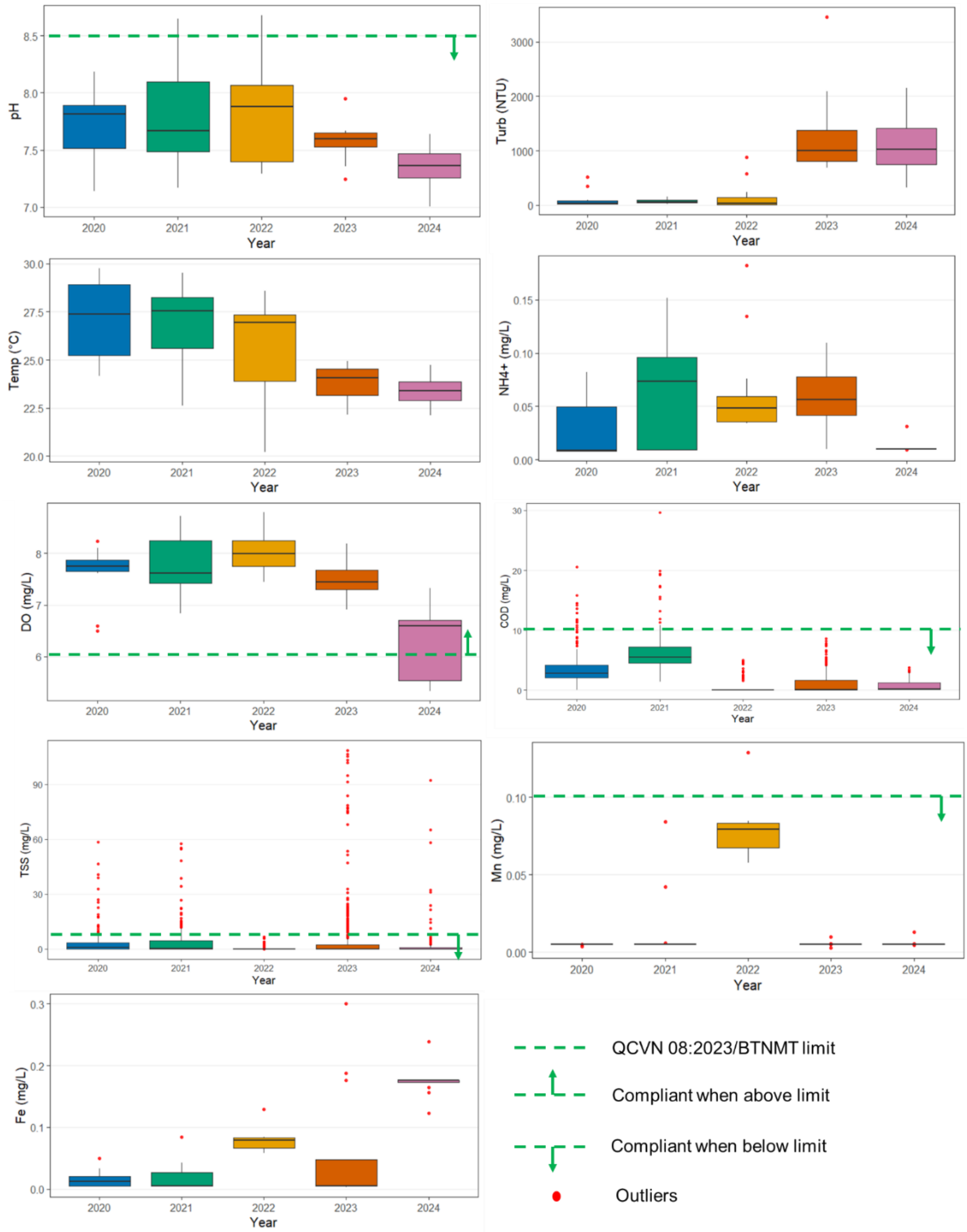

Figure 4. Interannual variability of selected water quality parameters in Bien Ho during 2020-2024. Boxes show the interquartile range (IQR), center lines indicate medians, whiskers represent 1.5 × IQR, and red points denote outliers. Green dashed lines indicate the corresponding QCVN 08:2023/BTNMT limits, with arrows denoting the direction of compliance. Parameters without threshold lines complied with the applicable standards throughout the monitoring period.

Fe and Mn concentrations were mostly low but displayed seasonal and interannual variability (Figs. 3 and 4). Mn showed several elevated values in 2022, whereas Fe increased more noticeably toward late 2023 and 2024. The observed variation may be linked to suspended matter, catchment inputs, and redox-sensitive behavior of these metals, as reported in previous lake water quality studies [21, 28]. Nevertheless, because sediment chemistry, redox potential, and vertical profiles were not measured in this study, the interpretation of Fe and Mn dynamics should remain cautious.

3.2. Seasonal and Interannual Statistical Patterns

The statistical analyses confirmed that temporal variability was a significant feature of the Bien Ho water quality dataset. ANOVA results showed that year had a significant effect on all measured parameters ($p < 0.05$), indicating marked interannual variability during 2020-2024. Seasonal effects were significant for most variables, with the strongest seasonal dependence observed for temperature, followed by turbidity, Mn, Fe, and DO. In contrast, pH, NH_4^+, TSS, and COD did not show statistically significant seasonal differences at $p < 0.05$. These results indicate that some parameters responded consistently to seasonal hydrological conditions, whereas others were more strongly influenced by short-term events or interannual variability.

The significant year effect suggests that water quality in Bien Ho was not stationary over the five-year monitoring period. Annual boxplots showed that several parameters became more variable during 2022-2024, particularly turbidity, TSS, Fe, Mn, and DO (Fig. 4). This period included the 29 September 2022 dam-breach event and subsequent years of hydrological adjustment. However, the statistical results alone do not isolate the dam-breach effect from other factors, such as rainfall variability, catchment runoff, or operational changes in the water system. Therefore, the observed post-2022 variability should be interpreted as an indication of increased hydrological and water quality sensitivity rather than direct proof of a single causal driver.

MANOVA results further indicated significant multivariate effects of year, season, and their interaction on the combined water quality dataset. This finding confirms that the overall structure of water quality differed among years and between seasons. The significant year-season interaction suggests that seasonal effects were not constant across the monitoring period. In practical terms, the rainy season or dry season behavior of water quality parameters varied among years, which is consistent with the influence of interannual climatic and hydrological variability in monsoon lake systems [2, 8, 22, 25].

The statistical results support the conclusion that Bien Ho water quality is controlled by both regular seasonal forcing and interannual variability. Seasonal forcing is mainly reflected by temperature, turbidity, DO, Fe, and Mn, whereas interannual variability is evident across the full parameter set. These patterns justify the use of multivariate methods to evaluate the combined behavior of water quality parameters rather than interpreting each variable separately.

3.3. Correlation Structure and PCA-derived Controls

Spearman correlation analysis revealed several significant relationships among the measured parameters (Fig. 5). COD was positively correlated with TSS, indicating that suspended particles and organic matter tended to increase together. This relationship is consistent with observations in other river and lake systems where runoff and resuspension can transport both particulate matter and associated organic substances [17, 22]. However, because COD and TSS in this study were derived from optical sensor signals, their relationship should also be interpreted with consideration of the sensor-based nature of both variables.

pH showed positive correlations with DO and temperature (Fig. 5). This association suggests that pH variability was linked to oxygenation and thermal conditions in the monitored water column. Similar relationships have been reported in lake systems where seasonal changes in temperature, biological activity, and gas exchange influence pH and DO dynamics [19, 23, 29]. Turbidity showed negative correlations with temperature and DO, indicating that periods with higher suspended-particle influence were generally associated with lower oxygenation and cooler or more disturbed hydrological conditions. This pattern is consistent with the seasonal contrast between relatively stable dry season conditions and runoff-influenced rainy season conditions.

The negative correlations of COD with Fe and Mn suggest that dissolved metal variability was not primarily associated with organic matter accumulation in the monitored dataset. Instead, Fe and Mn may reflect other processes, including particulate input or redox-sensitive release from sediments. This interpretation is consistent with the known behavior of Fe and Mn in lacustrine environments [21, 28], but it cannot be confirmed without direct measurements of sediment composition, redox potential, or vertical water column structure.

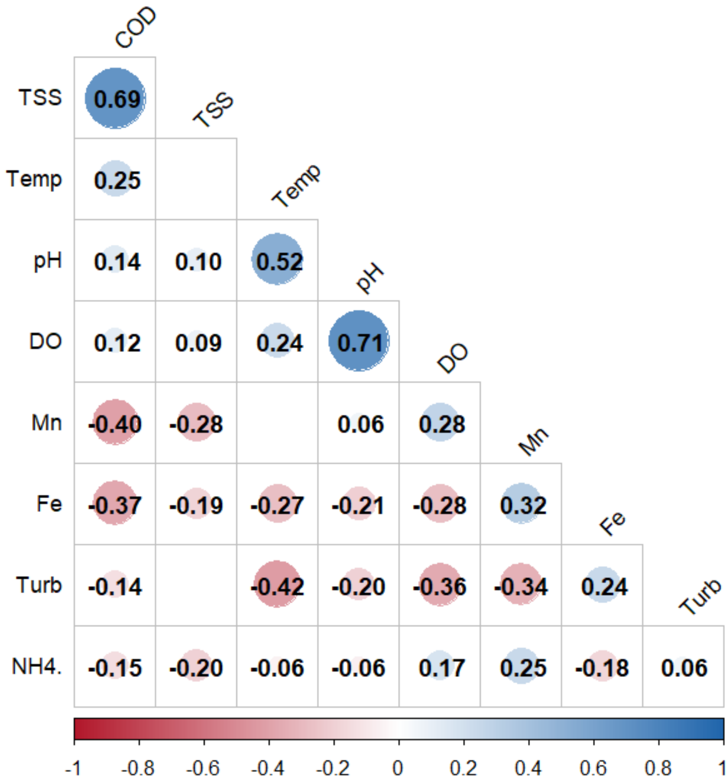

Figure 5. Spearman correlation matrix of physicochemical water quality parameters in Bien Ho.

PCA was used to identify the dominant multivariate structure of the dataset. The first two principal components explained 49.8% of the total variance, with Dim1 accounting for 29.6% and Dim2 for 20.2% (Fig. 6). Although this percentage does not represent the full variability of the system, it is sufficient to identify the main gradients present in the dataset. Dim1 was mainly associated with DO, pH, temperature, turbidity, and Fe, and can be interpreted as a hydro-physical and oxygenation gradient. Dim2 was mainly associated with Mn, TSS, and COD, reflecting a particulate-organic and redox-sensitive gradient.

The PCA biplot showed partial separation between rainy season and dry season samples (Fig. 6). Rainy season samples tended to align with turbidity and Fe, suggesting stronger influence of runoff, suspended particles, and mineral-related inputs during wet conditions. Dry season samples were more closely associated with DO, pH, and temperature, indicating relatively stable and oxygenated conditions in the monitored water column. These results are consistent with previous applications of PCA to water quality datasets, where principal components often reflect hydrological seasonality, suspended matter transport, and oxygen-related processes [15-17, 21, 22].

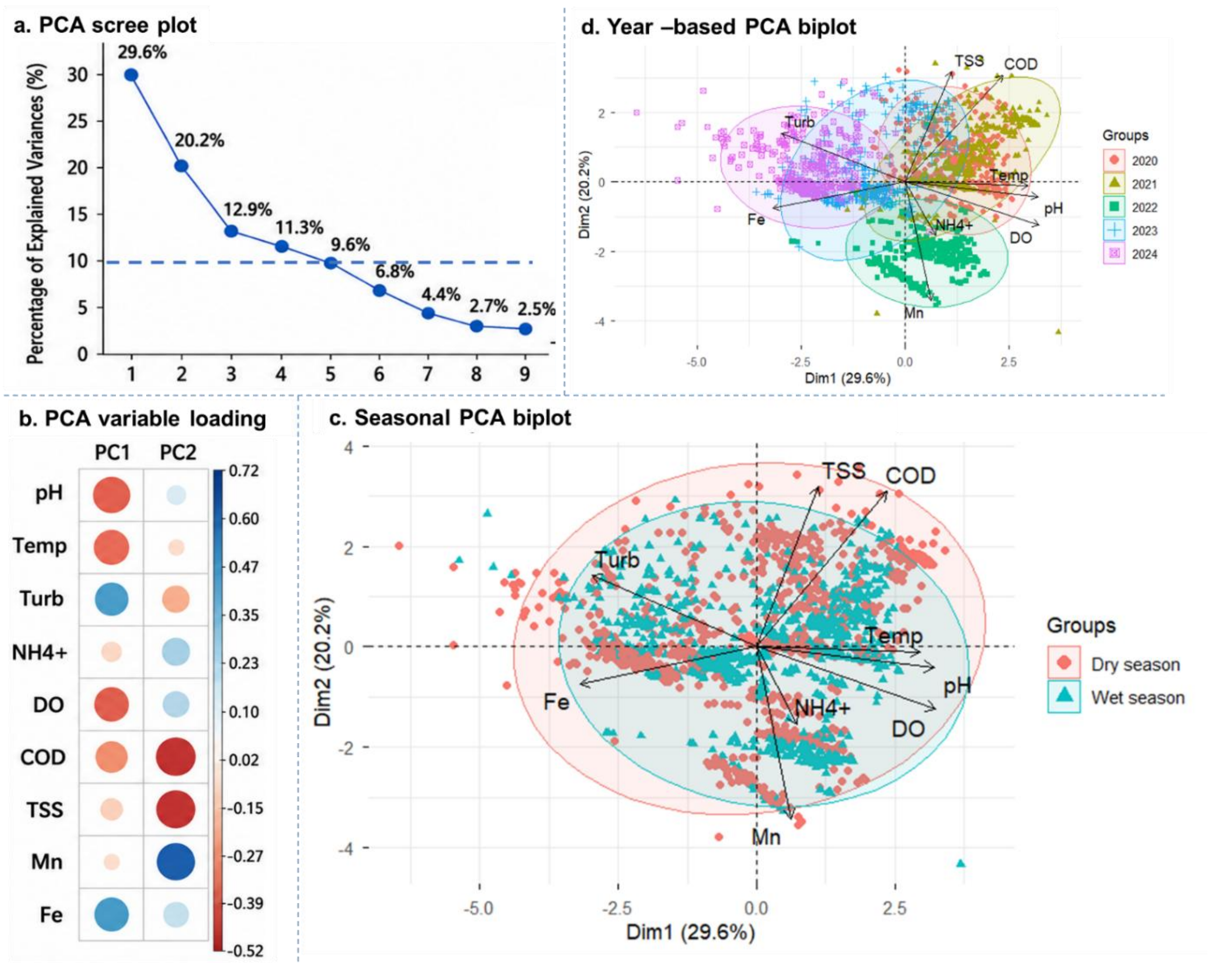

Figure 6. Principal Component Analysis (PCA) of water quality parameters in Bien Ho during 2020-2024: (a) PCA scree plot, (b) PCA variable loading, (c) seasonal PCA biplot, (d) year-based PCA biplot.

The PCA results should be interpreted as evidence of dominant statistical associations rather than direct proof of specific mechanisms. The two retained components captured the main structure of the observed dataset, but approximately half of the variance remained unexplained by Dim1 and Dim2. Therefore, additional factors not fully represented in the present dataset, such as rainfall intensity, water level, inflow-outflow dynamics, phytoplankton biomass, sediment chemistry, and vertical stratification, may also contribute to water quality variability.

3.4. Hydrological Disturbance and Management Implications

The breach of the regulating dam on 29 September 2022 represents an important hydrological disturbance in the study period. The event allowed irrigation water from a nearby reservoir to overflow into Bien Ho, potentially affecting suspended matter, turbidity, and catchment-derived inputs. The annual variability shown in Fig. 4 indicates that several parameters, particularly turbidity, TSS, Fe, Mn, and DO, showed increased variability during 2022-2024 compared with some earlier years. This temporal pattern suggests that the lake became more variable after the disturbance period.

However, the available data do not allow the dam-breach effect to be separated quantitatively from other drivers, such as rainfall variability, catchment erosion, wind-induced mixing, changes in water residence time, or anthropogenic inputs. Therefore, the dam-breach event should be discussed as a plausible contributing factor rather than as the sole cause of post-2022 water quality changes. A more rigorous assessment would require before-after comparison using hydrological data, rainfall records, water-level data, and information on inflow from the irrigation reservoir.

From a management perspective, the results indicate that Bien Ho generally maintained acceptable water quality for domestic water supply according to QCVN 08:2023/BTNMT, but the increased variability of turbidity, TSS, Fe, Mn, and DO highlights the need for continuous monitoring and early-warning capacity [6]. These parameters are particularly relevant because they respond to hydrological disturbance, suspended-particle input, and possible changes in oxygenation conditions. Maintaining the automatic monitoring system and integrating it with meteorological and hydrological observations would improve the ability to detect short-term anomalies and distinguish seasonal variation from disturbance-driven changes.

The PCA and correlation results also provide useful guidance for monitoring optimization. Turbidity and TSS represent particulate dynamics, COD and NH_4^+ reflect organic and nutrient-related conditions, DO and pH indicate oxygenation and acid-base status, while Fe and Mn may serve as indicators of mineral input or redox-sensitive behavior. Together, these parameters provide a practical monitoring framework for tracking changes in water quality under monsoon hydrology and catchment pressure.

3.5. Limitations of the Study

This study provides a useful assessment of temporal water quality variability in Bien Ho based on continuous monitoring data from 2020 to 2024. Nevertheless, several limitations should be recognized when interpreting the results. First, the dataset was obtained from a single automatic monitoring station. Therefore, the analysis represents temporal variability at the monitoring location and cannot fully describe spatial heterogeneity across the lake. Future studies should combine automatic monitoring with spatial sampling at different lake zones and depths.

Second, COD and TSS were derived from optical sensor signals rather than direct laboratory measurements. Although optical monitoring is suitable for high-frequency observation, sensor-based estimates may be affected by particle size, color, organic matter composition, biofouling, and calibration drift. Regular laboratory verification is therefore necessary to strengthen data reliability, particularly for parameters used in multivariate analysis.

Third, this study did not include continuous rainfall, water-level, inflow-outflow, or evaporation data for the entire 2020-2024 period. As a result, the influence of specific hydrological events, including the 29 September 2022 dam breach, could not be quantified directly. Integrating water quality monitoring with meteorological and hydrological datasets would allow more robust assessment of event-driven changes and seasonal controls.

Fourth, the interpretation of internal lake processes remains indirect. The discussion of redox-sensitive behavior of Fe and Mn, oxygenation, and sediment-water interaction is based on water-column indicators and statistical associations. Direct measurements of redox potential, vertical DO profiles, sediment chemistry, chlorophyll-a, and phytoplankton biomass would be needed to confirm the underlying mechanisms.

Finally, PCA explained 49.8% of the total variance using the first two components. This result identifies the main observable gradients in the dataset, but it also indicates that additional processes contributed to water quality variability. Therefore, PCA results should be used as an exploratory framework for identifying dominant patterns rather than as a complete explanation of the lake's hydrochemical dynamics.

4. Conclusions

This study assessed temporal water quality variability in Bien Ho during 2020-2024using continuous monitoring data and multivariate statistical analysis. The results showed that most physicochemical parameters remained within the limits of QCVN 08:2023/BTNMT, Column A, indicating that the lake generally maintained water quality suitable for domestic water supply after appropriate treatment. Nevertheless, clear seasonal and interannual variability was observed, particularly for turbidity, total suspended solids, dissolved oxygen, iron, and manganese.

Seasonal patterns reflected the influence of the tropical monsoon regime. Higher turbidity and episodic TSS increases were mainly observed during the rainy season and transition periods, whereas DO, pH, Fe, and Mn showed distinct temporal fluctuations across seasons and years. ANOVA and MANOVA confirmed significant effects of year, season, and their interaction on the water quality dataset, indicating that both seasonal forcing and interannual variability contributed to changes in lake water conditions.

Spearman correlation analysis showed a strong positive relationship between COD and TSS, suggesting coupled variability between suspended particles and organic matter indicators. Positive correlations among pH, DO, and temperature, together with negative associations between turbidity and DO, further indicated that oxygenation, thermal conditions, and suspended-particle dynamics were important components of water quality variability.

PCA identified two principal components explaining 49.8% of the total variance. The first component represented a hydro-physical and oxygenation gradient associated with temperature, DO, pH, turbidity, and Fe. The second component reflected a particulate-organic and redox-sensitive gradient characterized mainly by TSS, COD, and Mn. These components provide an exploratory framework for identifying the dominant temporal patterns in the monitoring dataset, although additional hydrological, biological, and sediment data would be required to confirm the underlying mechanisms.

Overall, the findings indicate that Bien Ho currently maintains generally favorable water quality conditions, but the increased variability observed in recent years highlights the need for sustained high-frequency monitoring. Future monitoring should integrate water quality data with rainfall, water level, inflow-outflow, sediment, and biological observations to improve early warning, support source-water protection, and strengthen the sustainable management of this strategic volcanic lake.

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