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Evaluation of Lake Sentani Water Quality Using Pollution Index, STORET, CCME-WQI, BC-WQI, and NSF-WQI Methods

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Abstract

Lake Sentani is the largest lake in Papua and serves as an important source of raw water, fisheries, and livelihoods for communities in Jayapura. Increasing anthropogenic pressures from settlements, agriculture, aquaculture, and tourism have raised concerns regarding the deterioration of its water quality. This study compared the water quality status of Lake Sentani using five assessment methods: Pollution Index (IP), STORET, CCME-WQI, BC-WQI, and NSF-WQI. Water samples were collected from five stations representing littoral, limnetic, and human-activity-influenced zones. The analyzed parameters included physical (temperature, TDS, TSS, turbidity, and Secchi depth), chemical (pH, dissolved oxygen, BOD_5, COD, nitrate, phosphate, ammonia, and sulfate), and biological (total coliform) indicators. The results indicated IP values ranging from 3.95 to 6.43 (lightly to moderately polluted), STORET scores from −20 to −44 (moderately to heavily polluted), CCME-WQI values from 47.3 to 71.2 (marginal to fair), BC-WQI values from 44.7 to 68.5, and NSF-WQI values from 46.1 to 70.3. Station S3 (Sentani Town) consistently exhibited the poorest water quality, whereas Station S4 (Ayapo) showed the best condition. Elevated BOD_5, phosphate, ammonia, and total coliform were identified as the principal parameters contributing to water quality degradation. The five assessment methods produced generally similar spatial patterns across the sampling stations, with Pearson correlation coefficients ranging from 0.89 to 0.97, although these correlations should be interpreted cautiously given the limited number of monitoring stations. Among the evaluated approaches, CCME-WQI provided a balanced assessment by integrating the scope, frequency, and magnitude of water quality exceedances, making it a suitable framework for routine monitoring of tropical lake ecosystems under the conditions examined in this study.

Keywords: lake sentani, water quality index, pollution index, STORET, CCME-WQI, tropical lake

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INTRODUCTION

Freshwater lakes are among the most vulnerable ecosystems to increasing anthropogenic pressures resulting from rapid urbanization, agricultural intensification, land-use change, and climate variability. These pressures accelerate nutrient enrichment, organic pollution, and ecological degradation, ultimately reducing the capacity of lakes to provide essential ecosystem services such as drinking water supply, fisheries, biodiversity conservation, and recreational functions. Consequently, maintaining water quality has become a major environmental priority and requires reliable assessment methods capable of accurately reflecting ecological conditions and supporting evidence-based management decisions (Uddin et al., 2021; United Nations Environment Programme

[UNEP], 2021). Water quality assessment has therefore evolved from simple parameter-based monitoring toward integrated index approaches that synthesize multiple physical, chemical, and biological indicators into comprehensive measures of environmental condition.

Tropical lakes are particularly susceptible to water quality deterioration because warm temperatures, intense rainfall, and continuous biological productivity accelerate nutrient cycling and eutrophication processes. Compared with temperate lakes, tropical aquatic ecosystems often exhibit greater temporal variability and stronger responses to anthropogenic disturbances, making comprehensive water quality assessment increasingly important (Banda & Kumarasamy, 2020; Uddin et al., 2021). Lake Sentani represents one of the most important tropical lake ecosystems in eastern Indonesia. Located in Papua Province, Lake Sentani covers approximately ±9,360 ha with an average depth of 24.5 m and a maximum depth of approximately 51 m. Administratively, the lake extends across Jayapura Regency and Jayapura City at coordinates 140°23'–140°38' E and 2°31'–2°41' S (Koibur et al., 2021). Besides supplying raw water for more than 300,000 residents, the lake also supports fisheries, tourism, transportation, and endemic biodiversity, including the endangered Sentani rainbow fish (Chilatherina sentaniensis).

Recent studies have reported increasing evidence of environmental degradation in Lake Sentani associated with expanding human activities. Rapid population growth around the lake, settlement expansion along the shoreline, agricultural and plantation runoff, tourism development, and intensive floating net cage (KJA) aquaculture have substantially increased nutrient and organic matter inputs into the lake ecosystem (Wambrauw et al., 2022; Suhartawan, 2025). Previous investigations have also reported increasing trophic status, elevated phosphate concentrations, declining dissolved oxygen in several areas, and growing risks of eutrophication that threaten ecological stability and aquatic biodiversity (Koibur et al., 2021). Similar patterns of nutrient enrichment and ecological degradation have been documented in many tropical lakes where continuous external nutrient loading stimulates excessive algal growth, oxygen depletion, and deterioration of ecosystem functions (Riyadi et al., 2023; Xiao et al., 2022). These findings indicate that continuous and scientifically robust monitoring is essential to support sustainable management of Lake Sentani.

Reliable water quality monitoring requires not only accurate measurements of individual physicochemical and biological parameters but also assessment frameworks capable of integrating multiple indicators into meaningful information for environmental management. In Indonesia, water quality status is officially evaluated using the Pollution Index (IP) and STORET methods as stipulated in the Decree of the Minister of Environment No. 115 of 2003 (Ministry of Environment of the Republic of Indonesia, 2003). At the international level, numerous Water Quality Index (WQI) approaches have been developed to integrate multiple water quality variables into a single interpretable metric, thereby facilitating environmental assessment, comparison, and communication among stakeholders (Ding et al., 2022; Wu et al., 2023; Kachroud et al., 2019). These approaches differ substantially in their mathematical formulations, parameter selection, weighting strategies, and treatment of water quality standard exceedances, which may lead to different interpretations of environmental conditions and influence subsequent management decisions (Wu et al., 2023; Ding et al., 2022).

Different water quality assessment methods may produce different classifications even when applied to the same monitoring dataset because they employ distinct computational algorithms, parameter weighting schemes, aggregation procedures, and approaches to evaluating compliance with water quality standards (Chidiac et al., 2023; Manna & Biswas, 2023; Swain, 2024). Consequently, the selection of an assessment method may influence the interpretation of ecological conditions and the prioritization of environmental management strategies, particularly when different indices respond differently to parameter exceedances and spatial variability (Babatunde, 2024; Ji et al., 2016). Comparative evaluation under identical environmental conditions is therefore essential to determine the consistency, robustness, and practical applicability of different assessment frameworks, especially for tropical lake ecosystems characterized by pronounced spatial and seasonal variability (Xiao et al., 2022; Swain, 2024).

The five assessment methods were selected because they represent complementary approaches widely applied in water quality evaluation. The Pollution Index and STORET methods are the two regulatory frameworks officially adopted for environmental monitoring in Indonesia and therefore remain essential for compliance-based assessments (Ministry of Environment, 2003). In contrast, CCME-WQI, BC-WQI, and NSF-WQI are internationally recognized indices that integrate multiple dimensions of water quality into composite scores suitable for broader environmental evaluation (CCME, 2017; Uddin et al., 2021). CCME-WQI evaluates water quality based on the scope, frequency, and amplitude of quality standard exceedances, whereas NSF-WQI applies parameter-specific weighting according to ecological significance (Brown et al., 1970; CCME, 2017). BC-WQI was included because it represents an adaptation of the CCME framework developed to improve the interpretation of water quality under different environmental monitoring conditions rather than because of similarities between British Columbia and tropical regions. Comparing these five methods under identical environmental conditions enables evaluation of their consistency, sensitivity, and practical applicability for tropical lake monitoring (Uddin et al., 2021; Banda & Kumarasamy, 2020).

Although numerous studies have investigated the water quality of Lake Sentani, previous research has primarily focused on individual physicochemical parameters, trophic status assessment, pollution sources, or the application of a single water quality index (Koibur et al.,2021; Suhartawan, 2025). Similar tendencies have also been reported in studies of other tropical lakes, where water quality assessments generally rely on individual indices without evaluating the consistency among multiple assessment frameworks (Banda & Kumarasamy, 2020; Uddin et al., 2021). Consequently, it remains unclear whether different assessment methods produce consistent classifications when applied to the same monitoring dataset and which framework provides the most appropriate basis for routine monitoring of tropical lake ecosystems. This methodological limitation restricts evidence-based selection of appropriate assessment tools for environmental monitoring and may lead to different interpretations of water quality status depending on the index employed (Sutadian et al., 2016). A systematic comparison of multiple assessment methods under identical environmental conditions is therefore required to better understand their respective strengths, limitations, and applicability for supporting environmental management.

The novelty of this study lies in the simultaneous application and comparative evaluation of five widely used water quality assessment methods Pollution Index, STORET, CCME-WQI, BC-WQI, and NSF-WQI using the same monitoring dataset from Lake Sentani. Unlike previous studies that relied on individual parameters or single-index approaches, this study evaluates the consistency, sensitivity, and practical applicability of multiple assessment frameworks for tropical lake ecosystems. Accordingly, this study aims to (1) analyze the water quality status of Lake Sentani using five assessment methods simultaneously, (2) compare the consistency and differences among these methods, and (3) evaluate their applicability for supporting routine monitoring and environmental management of tropical lakes in Papua.

METHOD

Study Area and Sampling

This study was conducted in Lake Sentani, Jayapura Regency, Papua Province, Indonesia, between March and August 2024, encompassing both the rainy and dry seasons. Lake Sentani is the largest freshwater lake in Papua and exhibits considerable spatial heterogeneity due to variations in hydrological characteristics, surrounding land use, and anthropogenic activities. Therefore, five sampling stations were purposively selected to represent the principal ecological zones of the lake, including littoral and limnetic areas, as well as locations predominantly influenced by agricultural runoff, urban settlements, floating net cage aquaculture, and relatively undisturbed environments (Lumb et al., 2011). Water samples were collected from all sampling stations using a consistent sampling protocol throughout the study period. Samples were obtained from the surface layer (0–0.5 m) and the middle water column, after which the measurements were integrated to represent the overall water quality conditions at each station. The resulting dataset served as the basis for calculating the Pollution Index (IP), STORET, CCME-WQI, BC-WQI, and NSF-WQI. **Figure 1** presents the spatial distribution of the sampling stations. The characteristics of each sampling station are summarized in **Table 1**.

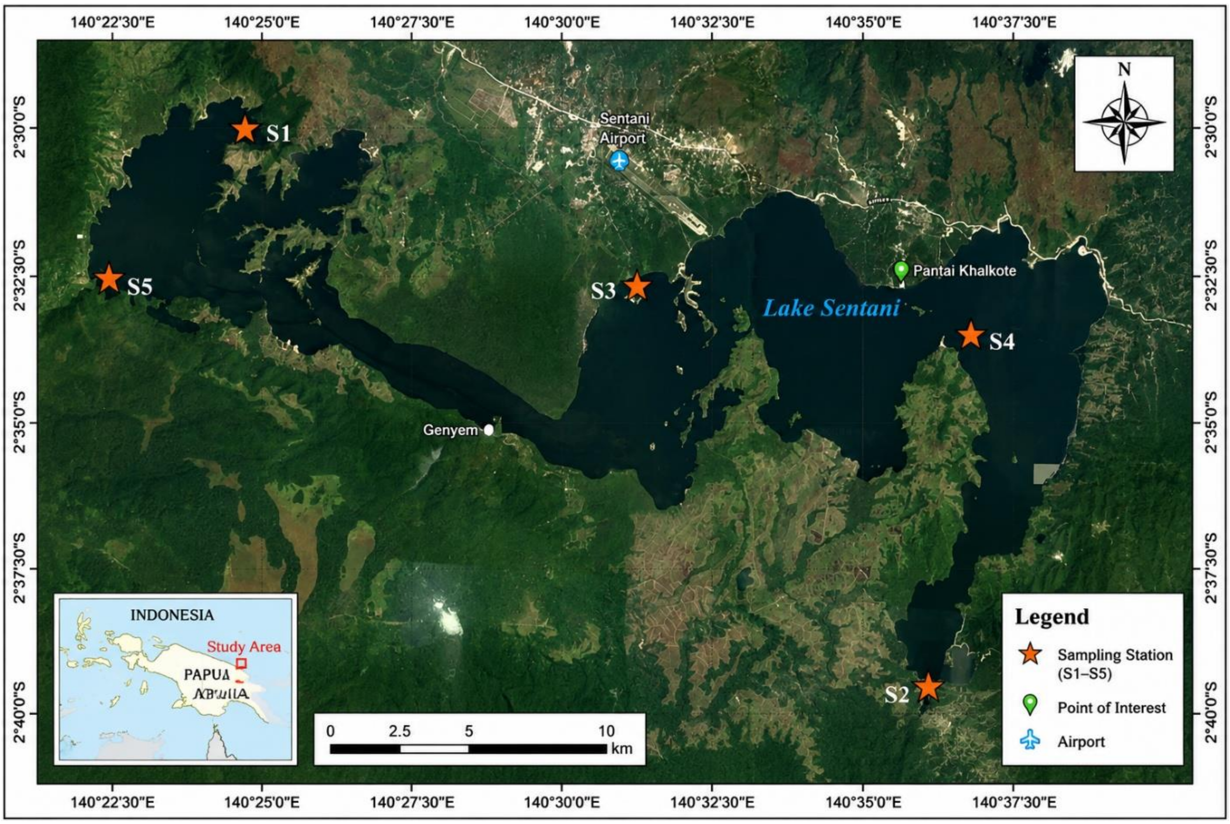

Figure 1. Location of the five water sampling stations in Lake Sentani, Jayapura, Papua, Indonesia

Table 1. Geographic Coordinates and Characteristics of Water Sampling Stations

Code	Location	Coordinate	Description
S1	Dosay	140°24'15' E, 2°35'42' S	Western littoral zone, near the mouth of the Dosay River, agricultural influence
S2	Puay	140°28'33' E, 2°32'18' S	The north-central zone, near the traditional village on the water
S3	Sentani Kota	140°31'08' E, 2°34'56' S	Eastern littoral zone, near city center, high domestic pressure
S4	Ayapo	140°35'44' E, 2°33'21' S	The eastern limnetic zone, relatively far from human activity
S5	Yakonde	140°33'19' E, 2°37'05' S	Southern zone, influence of KJA (floating net cage)

Water Quality Sampling and Laboratory Analysis

Water samples were collected from each sampling station using a Kemmerer water sampler at two sampling depths, namely the surface layer (0–0.5 m) and the middle water column, to represent the vertical variation of water quality within the lake. Physical parameters, including temperature, pH, dissolved oxygen (DO), total dissolved solids (TDS), and turbidity, were measured in situ using a calibrated YSI Pro Plus multiparameter probe. Water transparency was determined using a 30-cm Secchi disk, whereas samples intended for chemical and microbiological analyses were preserved according to the relevant Indonesian National Standards (SNI) and transported to the Environmental Health Laboratory of the Papua Provincial Health Office for subsequent laboratory analysis.

Laboratory analyses were conducted following standardized analytical procedures specified in the corresponding SNI methods to ensure consistency and reliability of the measurements. Instrument calibration and sample preservation were performed in accordance with laboratory protocols before analysis, and all measurements were completed within the recommended holding times prescribed by the applicable analytical standards. The physical, chemical, and microbiological parameters analyzed in this study, together with their analytical methods and the corresponding water quality standards based on Government Regulation of the Republic of Indonesia No. 22 of 2021 (Class II), are summarized in **Table 2**.

Table 2. Water Quality Parameters, Analysis Methods, and Quality Standards Based on Government Regulation 22 of 2021

No.	Parameter	Analysis Method	Quality Standards (PP 22/2021, Class II)
1	Temperature (°C)	In situ, thermometer	Deviasi 3°C
2	pH	Electrometry, SNI 06-6989.11	6–9
3	DO (mg/L)	Winkler/Electrometry	≥4
4	BOD5 (mg/L)	Winkler, SNI 6989.72	≤3
5	COD (mg/L)	Open reflux, SNI 6989.2	≤25
6	TSS (mg/L)	Gravimetric method, SNI 6989.3	≤50
7	Nitrate (mg/L)	Spectrophotometer, SNI 6989.79	≤10
8	Phosphate (mg/L)	Spectrophotometer, SNI 06-6989.31	≤0.2
9	Ammonia-N (mg/L)	Nessler, SNI 6989.30	≤0.5
10	Total Coliform (MPN/100 mL)	MPN/tube, SNI 01-2332.1	≤1000
11	TDS (mg/L)	Gravimetric method	≤1000
12	Turbidity (NTU)	Nephelometric method	–

Water Quality Assessment Methods

To obtain a comprehensive evaluation of water quality status, five assessment methods representing both Indonesian regulatory approaches and internationally recognized Water Quality Index (WQI) frameworks were applied. The Pollution Index (IP) and STORET methods were selected because they constitute the official water quality assessment approaches stipulated by the Indonesian Ministry of Environment (Ministry of Environment, 2003). Meanwhile, CCME-WQI, BC-WQI, and NSF-WQI were included because they employ different computational concepts, parameter weighting systems, and assessment philosophies that enable comparison of methodological consistency and applicability under tropical lake conditions (Sutadian et al., 2016; CCME, 2017).

The Pollution Index (IP), developed by Nemerow and Sumitomo and adopted by the Indonesian Ministry of Environment (2003), evaluates water quality by comparing measured concentrations with corresponding water quality standards.

$$IP = \sqrt{\frac{\left(\frac{C_i}{L_{ij}}\right)_M^2 + \left(\frac{C_i}{L_{ij}}\right)_R^2}{2}} \quad (1)$$

Where, the classification criteria are:
IP ≤ 1.0 : Good
1.0 < IP ≤ 5.0 : Lightly polluted
5.0 < IP ≤ 10.0 : Moderately polluted
IP >10 : Heavily polluted

The STORET method evaluates compliance with water quality standards by assigning penalty scores to parameters exceeding regulatory thresholds (Ministry of Environment, 2003). The cumulative score determines the overall water quality status according to the national classification system. A score of 0 indicates that the water quality meets the standard, scores from −1 to −10 indicate lightly polluted conditions, scores from −11 to −30 indicate moderately polluted conditions, scores from −31 to −50 indicate heavily polluted conditions, and scores of ≤−51 indicate very heavily polluted conditions.

The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) evaluates water quality based on three components:
F1 (Scope) : percentage of variables exceeding standards.
F2 (Frequency) : percentage of individual tests exceeding standards.
F3 (Amplitude) : magnitude by which failed tests exceed standards.
The final index was calculated according to the CCME (2017) guideline. CCME-WQI formula:

$$CCME - WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \quad (2)$$

The classification criteria are:
95-100 : Excellent
80-94 : Good
65-79 : Fair
45-64 : Marginal
0-44 : Poor

BC-WQI represents the original provincial water quality index developed in British Columbia, which subsequently served as the conceptual foundation for the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) (Swain, 2024). While both approaches evaluate water quality based on the extent of guideline exceedance, the CCME-WQI refines the original framework by integrating the scope, frequency, and amplitude of exceedances into a standardized national assessment system (CCME, 2017).

NSF-WQI Method. The National Sanitation Foundation WQI uses nine main parameters (DO, coliform, pH, BOD, nitrate, phosphate, temperature, turbidity, TDS) which are each multiplied by a certain weight based on the importance rating of the results of the expert survey. NSF-WQI is calculated as a weighted average (Sutadian et al., 2016):

$$NSF - WQI = \sum(i = 1)^n (w_i \times q_i) \quad (3)$$

where wi is the weight of the i-i parameter and qi is the quality value of the sub-index obtained from the NSF conversion curve. Ratings: 90–100 (Excellent), 70–89 (Good), 50–69 (Medium), 25–49 (Bad), 0–24 (Very Bad) (Brown et al., 1970).

Data Analysis

The measurement data was analyzed descriptively to determine the distribution of parameter values in each station. The correlation between the five assessment methods was tested using the Pearson (r) and Spearman (ρ) correlation at a confidence level of 95% (α = 0.05). Hierarchical cluster analysis (Ward method, Euclidean distance) was applied to group stations based on the similarity of their water quality profiles. All data processing is carried out using IBM SPSS Statistics 26 software and Microsoft Excel 2019.

RESULTS AND DISCUSSION

Water Quality Parameter Conditions of Lake Sentani

The measured physical, chemical, and microbiological water quality parameters at the five sampling stations are summarized in **Table 3**. The selected parameters represent key indicators commonly used to evaluate the ecological condition of freshwater ecosystems and to assess compliance with the Class II water quality standards established by Government Regulation No. 22 of 2021. Spatial variations among sampling stations provide an overview of the influence of different anthropogenic activities and hydrological characteristics on the water quality status of Lake Sentani.

Table 3 demonstrates considerable spatial variability in water quality across Lake Sentani. Among the five monitoring stations, S3 (Sentani Town) consistently exhibited the poorest water quality, as indicated by the highest concentrations of BOD_5 (5.9 mg/L), COD (31.2 mg/L), phosphate (0.42 mg/L), ammonia (0.71 mg/L), and total coliform (2,400 MPN/100 mL). Conversely, S4 (Ayapo) displayed the best overall water quality, characterized by the lowest concentrations of organic and nutrient-related pollutants and compliance with nearly all applicable water quality standards. Most measured parameters remained within the permissible limits, whereas BOD_5, COD, phosphate, ammonia, and total coliform exceeded the regulatory thresholds at several stations, indicating localized deterioration associated with human activities (Nugroho et al., 2020).

The poor water quality observed at S3 is closely associated with the high intensity of anthropogenic activities surrounding Sentani Town. Dense residential settlements, domestic wastewater discharge, commercial activities, and inadequate sanitation infrastructure collectively contribute substantial organic matter and nutrient inputs to the lake. In addition, the relatively enclosed shoreline configuration and limited water circulation in this section of the lake may reduce pollutant dispersion, thereby promoting the accumulation of organic pollutants. These environmental conditions are reflected by elevated BOD_5, which indicates high biodegradable organic loads, together with increased phosphate and ammonia concentrations that are commonly associated with untreated domestic wastewater and agricultural runoff. Similarly, the high total coliform concentration suggests fecal contamination resulting from inadequate sanitation practices in lakeside settlements. These findings are consistent with previous studies reporting increasing anthropogenic pressures and declining water quality in Lake Sentani (Koibur et al., 2021; Riyadi et al., 2023; Suhartawan, 2025).

Table 3. Water Quality Parameters at the Five Sampling Stations in Lake Sentani

Parameter	S1	S2	S3	S4	S5	Mean	Quality Standard
Temperature (°C)	28.4	28.9	29.6	27.8	28.7	28.7	±3°C deviation
pH	7.1	7.3	7.6	7.0	7.2	7.2	6–9
DO (mg/L)	5.2	4.8	4.1	6.3	4.9	5.1	≥4
BOD5 (mg/L)	3.8*	4.5*	5.9*	2.1	4.2*	4.1	≤3
COD (mg/L)	18.4	23.7	31.2*	12.8	22.1	21.6	≤25
TSS (mg/L)	24.3	31.7	38.4	18.6	28.9	28.4	≤50
Nitrate (mg/L)	2.14	2.87	3.52	1.45	2.63	2.52	≤10
Phosphate (mg/L)	0.24*	0.31*	0.42*	0.15	0.28*	0.28	≤0.2
Ammonia (mg/L)	0.38	0.52*	0.71*	0.22	0.47	0.46	≤0.5
T. Coliform (MPN/100 mL)	920	1.350*	2.400*	420	1.180*	1.254	≤1.000
TDS (mg/L)	148	167	195	121	158	158	≤1.000

Note: Values marked with an asterisk () exceed the Class II water quality standards specified in Government Regulation No. 22 of 2021*

Among the measured variables, BOD_5, phosphate, ammonia, and total coliform were identified as the principal parameters contributing to water quality deterioration. Elevated BOD_5 indicates increased microbial decomposition of organic matter, which can reduce dissolved oxygen availability and adversely affect aquatic organisms. Excessive phosphate concentrations accelerate nutrient enrichment and increase the risk of eutrophication, while elevated ammonia concentrations reflect the decomposition of nitrogen-containing organic materials and untreated wastewater inputs. High total coliform concentrations further indicate microbiological contamination associated with domestic sanitation deficiencies. Similar responses have been widely reported in tropical freshwater ecosystems experiencing increasing urbanization and nutrient enrichment (Uddin et al., 2021; Xiao et al., 2022). Nutrient enrichment in lake ecosystems can increase trophic status and accelerate eutrophication processes, as reported in previous lake studies in Indonesia (Sisinggih et al., 2022; Riyadi et al., 2023).

Water Quality Status Based on the Pollution Index (IP) and STORET Methods

The water quality status of Lake Sentani assessed using the Pollution Index (IP) and STORET methods is presented in **Figure 2**. Both methods consistently identified spatial differences in water quality among the five monitoring stations, although slight variations in pollution classification were observed because of differences in their assessment principles. The Pollution Index values ranged from 3.95 at S4 (Ayapo) to 6.43 at S3 (Sentani Town). Based on the classification established by the Indonesian Ministry of Environment (Ministry of Environment, 2003), S3 was classified as moderately polluted, whereas the remaining stations were categorized as lightly polluted. The elevated Pollution Index at S3 was primarily associated with the simultaneous exceedance of several critical parameters, including BOD_5, COD, phosphate, ammonia, and total coliform, indicating that this area experiences the greatest cumulative anthropogenic pressure. In contrast, S4 exhibited the lowest IP value because nearly all measured parameters complied with the applicable water quality standards.

The STORET scores ranged from −20 at S4 to −44 at S3. According to the national STORET classification, S1 and S4 were categorized as moderately polluted, whereas S2, S3, and S5 were classified as heavily polluted. These results indicate that several stations experienced cumulative exceedances across multiple water quality parameters, particularly BOD_5, phosphate, total coliform, and ammonia, which are widely recognized as indicators of organic pollution, nutrient enrichment, and domestic wastewater contamination associated with intensive human activities.

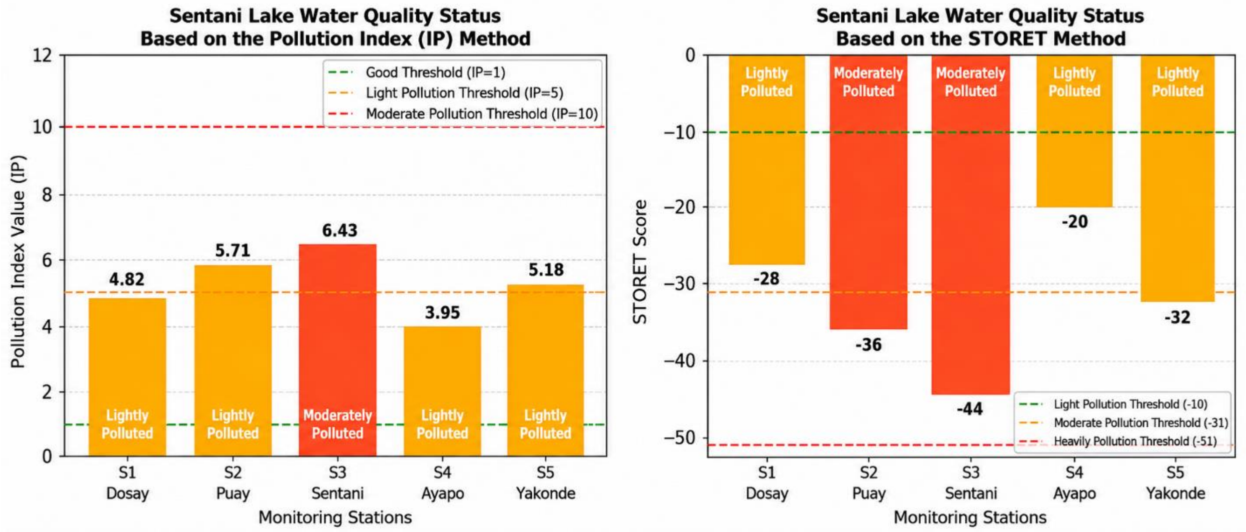

Figure 2. Comparison of Pollution Index (IP) Values and STORET Scores Between Stations

Although both methods identified S3 as the most degraded location and S4 as the least polluted, slight differences in their classifications were observed for several stations. These differences arise from the distinct computational concepts employed by the two methods. The Pollution Index emphasizes the magnitude of the highest concentration-to-standard ratio while simultaneously considering the overall average exceedance, making it particularly sensitive to parameters with extreme values. In contrast, STORET assigns cumulative penalty scores for each parameter exceeding the regulatory threshold, thereby reflecting the combined effect of multiple violations rather than emphasizing a single dominant parameter. Consequently, stations exhibiting moderate exceedances across several parameters may receive different classifications depending on the assessment framework applied. Similar methodological differences between IP and STORET have been reported in previous comparative studies of surface water quality assessment in Indonesia (Sutadian et al., 2016; Tyagi et al., 2013).

Water Quality Status Based on CCME-WQI, BC-WQI, and NSF-WQI

The results of the three internationally recognized Water Quality Index methods are presented in **Figure 3**. Although the three indices produced slightly different numerical values, they consistently identified similar spatial patterns of water quality across Lake Sentani.

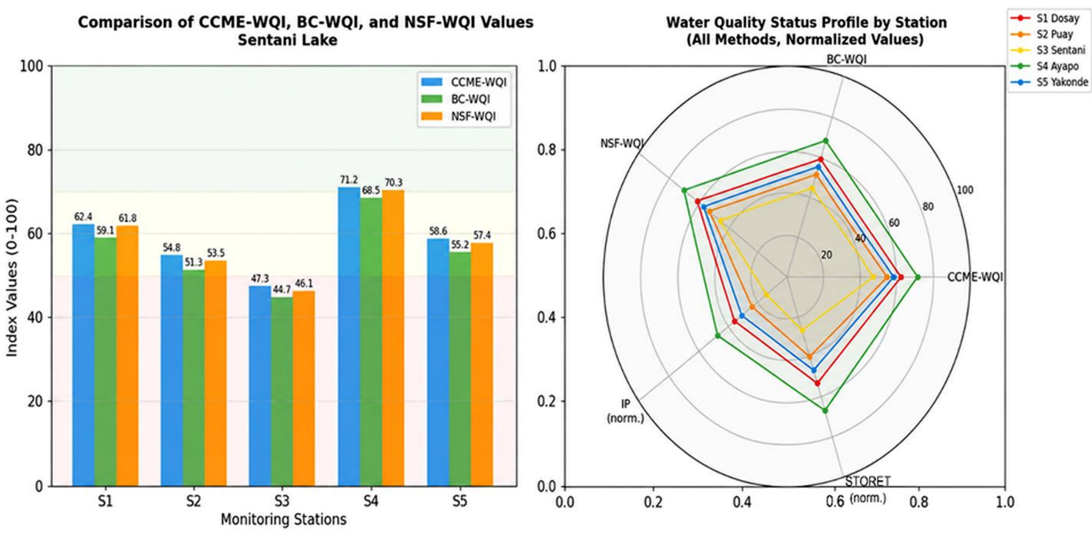

Figure 3. Comparison of CCME-WQI, BC-WQI, and NSF-WQI Values and Quality Status Profiles of Each Station

The CCME-WQI values ranged from 47.3 at S3 to 71.2 at S4, indicating water quality conditions varying from marginal to fair. Similarly, BC-WQI values showed the same spatial tendency, although scores were consistently slightly lower than those produced by CCME-WQI at stations experiencing greater pollution. Meanwhile, NSF-WQI values ranged from 46.1 to 70.3, generally falling between the CCME-WQI and BC-WQI scores. Despite these numerical differences, all three methods consistently identified S3 as the station with the poorest water quality and S4 as the least impacted site, demonstrating broad agreement regarding the spatial distribution of water quality conditions throughout the lake.

The observed differences among the three indices primarily reflect their distinct computational approaches. CCME-WQI evaluates water quality based on the scope, frequency, and amplitude of water quality standard exceedances, thereby providing an integrated assessment of overall environmental condition. BC-WQI, which was derived from the CCME framework, applies a modified evaluation procedure intended to improve the interpretation of repeated exceedances under different monitoring conditions. Consequently, BC-WQI generally produced slightly lower scores at stations where multiple parameters repeatedly exceeded regulatory thresholds. In contrast, NSF-WQI calculates the final index using parameter-specific weighting factors, assigning greater influence to variables considered ecologically important, particularly dissolved oxygen and BOD_5 (Brown et al., 1970; Sutadian et al., 2016). As a result, stations characterized by elevated organic pollution and reduced oxygen availability, especially S3, received relatively lower NSF-WQI scores than those produced by the other two indices.

The similarity in spatial patterns among the three methods suggests that, despite methodological differences, all indices respond consistently to the dominant pollution sources affecting Lake Sentani. The consistently poor performance of S3 reflects intensive urban activities, untreated domestic wastewater discharge, and nutrient enrichment, whereas the favorable condition of S4 is associated with lower anthropogenic disturbance and better water circulation. Comparable findings have been reported for tropical lakes where nutrient enrichment and organic pollution are concentrated near densely populated shoreline areas (Uddin et al., 2021; Banda & Kumarasamy, 2020).

From a management perspective, the three international indices provide complementary information rather than competing assessments. CCME-WQI offers a balanced representation of regulatory exceedances, NSF-WQI emphasizes ecologically significant parameters through weighted aggregation, and BC-WQI provides additional sensitivity to repeated water quality degradation. Therefore, the combined application of these indices facilitates a more comprehensive understanding of water quality conditions than reliance on a single assessment method alone.

Comparison and Correlation Among Assessment Methods

To further examine the agreement among the five assessment approaches, the relationships between the Pollution Index (IP), STORET, CCME-WQI, BC-WQI, and NSF-WQI were evaluated using Pearson correlation analysis. The correlation matrix is presented in **Table 4**, which summarizes the degree of association among the five assessment methods.

Table 4. Pearson correlation coefficients among the five water quality assessment methods

Metode	IP	STORET	CCME-WQI	BC-WQI	NSF-WQI
IP	1.00	0.97	-0.94	-0.92	-0.93
STORET	0.97	1.00	-0.95	-0.93	-0.94
CCME-WQI	-0.94	-0.95	1.00	0.97	0.96
BC-WQI	-0.92	-0.93	0.97	1.00	0.97
NSF-WQI	-0.93	-0.94	0.96	0.97	1.00

Note: STORET refers to the transformed pollution score, calculated using the absolute value of the original STORET score. Higher STORET values indicate poorer water quality. Correlation coefficients are interpreted cautiously because the analysis was based on five sampling stations.

The correlation analysis revealed that the five assessment methods generally exhibited similar spatial patterns in evaluating the water quality status of Lake Sentani. Positive correlations were observed among the three international water quality indices (CCME-WQI, BC-WQI, and NSF-WQI), whereas negative correlations were identified between these indices and the Pollution Index (IP). This inverse relationship is expected because higher IP values indicate poorer water quality, while higher WQI values represent better environmental conditions. Consequently, stations receiving high pollution scores under the IP method tend to obtain lower WQI scores.

The relationship between the Pollution Index (IP) and STORET should be interpreted in the context of their fundamentally different assessment frameworks. The Pollution Index quantifies water quality degradation based on the magnitude of deviation from regulatory standards, whereas the STORET method applies cumulative penalty scores to parameters that exceed prescribed thresholds. Consequently, numerical scores generated by the two methods are not directly comparable, although both approaches consistently identified the same spatial distribution of water quality across Lake Sentani, with S3 (Sentani Town) representing the most degraded station and S4 (Ayapo) exhibiting the best overall water quality. Similar differences among water quality indices have been reported in previous comparative studies, where methodological variations in parameter aggregation and scoring systems produced different numerical outputs while maintaining consistent spatial patterns of environmental quality (Al Yousif, 2023; Anastasopoulos, 2025).

Despite the relatively high correlation coefficients observed in this study, the results should be interpreted cautiously because the analysis was based on only five monitoring stations. Correlation analysis primarily reflects the degree of agreement in spatial patterns rather than demonstrating methodological equivalence or confirming that different assessment methods are interchangeable. Previous reviews have likewise emphasized that individual water quality indices differ in parameter selection, weighting strategies, aggregation procedures, and intended management objectives, and therefore should be regarded as complementary rather than substitutable assessment tools (Chidiac et al., 2023; Lokman et al., 2025).

The comparative evaluation indicates that each assessment method possesses distinct advantages depending on the intended monitoring objective. The Pollution Index (IP) and STORET methods remain the primary assessment frameworks for regulatory compliance in Indonesia because both are officially adopted under the national water quality assessment guidelines (Ministry of Environment, 2003). These methods are therefore essential for environmental reporting and regulatory decision-making. However, their primary focus on compliance with water quality standards may provide limited information regarding broader ecological conditions and temporal environmental variability. Among the three international indices, CCME-WQI provided the most balanced representation of water quality conditions across the five monitoring stations. Unlike NSF-WQI, which depends on predetermined parameter weights, or BC-WQI, which incorporates additional persistence-related considerations, CCME-WQI integrates the scope, frequency, and amplitude of water quality standard exceedances into a single assessment framework. This approach enables a comprehensive evaluation of overall water quality while remaining sufficiently flexible to accommodate different monitoring programs and parameter combinations (CCME, 2017; Sutadian et al., 2016).

The selection of CCME-WQI as the most suitable method in this study was based on several practical considerations. First, it demonstrated high sensitivity in distinguishing spatial variations among sampling stations. Second, it effectively integrates multiple water quality parameters without requiring subjective parameter weighting. Third, its computational framework is sufficiently flexible for routine monitoring programs involving different numbers of parameters and sampling frequencies. Finally, the resulting index is relatively straightforward to interpret and communicate to environmental managers and other stakeholders, thereby supporting evidence-based decision-making for tropical lake management.

Nevertheless, the recommendation of CCME-WQI should not be interpreted as replacing the Pollution Index or STORET methods. Instead, these methods should be regarded as complementary assessment tools serving different purposes. While IP and STORET remain indispensable for regulatory reporting and compliance with Indonesian environmental regulations, CCME-WQI provides additional scientific value for evaluating overall ecological conditions and long-term monitoring trends. The combined application of regulatory and international assessment frameworks therefore offers a more comprehensive basis for water quality evaluation and environmental management of Lake Sentani than reliance on a single method alone.

CONCLUSION

This study demonstrated that the five water quality assessment methods, namely the Pollution Index (IP), STORET, CCME-WQI, BC-WQI, and NSF-WQI, produced generally consistent spatial patterns in evaluating the water quality status of Lake Sentani despite their different computational approaches. Across all methods, Sentani Town (S3) was consistently identified as the most degraded sampling station, whereas Ayapo (S4) exhibited the most favorable water quality conditions. Water quality deterioration was primarily associated with elevated concentrations of BOD_5, phosphate, ammonia, and total coliform, indicating that domestic wastewater discharge, nutrient enrichment, and inadequate sanitation constitute the principal sources of pollution affecting the lake. These findings demonstrate that localized anthropogenic pressures play a dominant role in shaping the spatial distribution of water quality within Lake Sentani. The comparative evaluation further indicates that each assessment method provides complementary information for water quality monitoring. The Pollution Index and STORET methods remain essential for regulatory assessment in accordance with Indonesian environmental regulations, whereas CCME-WQI offers a flexible and integrated framework for scientific assessment by incorporating multiple dimensions of water quality into a single index. Accordingly, CCME-WQI is recommended as a complementary tool for routine environmental monitoring rather than as a replacement for the nationally mandated assessment methods. Because the inter-method comparison was based on a limited number of monitoring stations, the observed agreement among methods should be interpreted with appropriate caution and verified through future studies involving broader spatial coverage and repeated temporal observations. From a management perspective, the findings highlight Sentani Town (S3) as the highest priority area for pollution mitigation. Management efforts should therefore focus on reducing untreated domestic wastewater discharge, improving sanitation infrastructure in lakeside settlements, controlling nutrient inputs from surrounding land uses, and strengthening routine water quality monitoring to prevent further ecological degradation. Implementing these measures in combination with complementary assessment approaches is expected to provide a more robust scientific basis for sustainable management and conservation of Lake Sentani and other tropical freshwater ecosystems.

AUTHOR CONTRIBUTIONS

Conceptualization, BS; methodology, BS, and D; software, BS, and D; validation, BS; formal analysis, BS, and D; investigation, BS, and D; resources, BS, and D; data curation, BS, and D; writing—original draft preparation, BS, and D; writing—review and editing, BS, and D; visualization, BS, and D; supervision, BS, and D; project administration, BS; funding acquisition, BS.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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