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Development of a Multi-Indicator Assessment Framework for Evaluating Ecological Recovery in Polluted Lakes

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Abstract: Assessment of ecological recovery in polluted lakes is a large yet difficult task because traditional approaches of water quality evaluation cannot discern interactions between chemical, physical, biological and functional components of ecosystems, which are highly dynamic and complex. In this study, Multi-Indicator Assessment Framework (MIAF) was developed for evaluating the ecological recovery of polluted lakes by systematically quantifying variation in water quality, sediment quality, biological diversity and ecosystem functioning in lake ecosystems into a single unified system. Ecological indicators in the MIAF were first normalized, weighed equally in a group and then combined in to one index - the Composite Ecological Recovery Index (CERI). Based on its values, lakes can be classified into five recovery levels, i.e., seriously degraded lake, weak recovery lake, moderate recovery lake, strong recovery lake and highly recovered lake. Four lakes with various degrees of pollution and restoration status were tested, and the obtained CERI values ranged from 18.75 to 93.50, respectively. Additionally, quarterly monitoring indicated that actively restored lake showed a 21.35-point increase in CERI value over 4 sequential quarters, suggesting that the lake is undergoing ecological recovery. The results indicate that single-parameter assessment based only on conventional water quality conditions cannot sufficiently measure the progress of ecological restoration, but multi-parameter ecological assessment based on all four ecological indicators is more comprehensive in measuring the status of lake ecosystems. This framework can be effectively used for inter-lake comparison, deciphering the role of lake restoration processes, and systematic monitoring of restoration effectiveness. Overall, it can offer a transparent and flexible decision support method for evidence-based lake restoration and sustainable freshwater management.

Keywords: Lake Restoration; Ecological Recovery; Water Quality; Sediment Pollution; Biodiversity; Composite Index; Ecosystem Health.

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I. Introduction

Freshwater lakes shape hydrology, are carbon sinks, and sustain fisheries and diverse aquatic ecosystems. As freshwater lakes become heavily impacted by industrial waste, agricultural run-off, sewage, and urbanization, a complex web of effects develops. Pollutants damage water chemistry by oxygen depletion and nutrient overload, settle in sediments as long-lasting metal compounds and organic matter, and reduce populations of sensitive species. These stressors weaken the vital functions of lakes such as productivity, decomposition, and retention of nutrients, as well as the range of benefits that they offer (Dong et al., 2025; Weng et al., 2025).

Traditional assessments of lakes tend to focus on physicochemical water quality. But gains in water quality don't always mean the ecosystem is fully recovered. Biological communities and sediment pollution levels tend to change more gradually than water measures, as sediment contains legacy pollutants and recolonization is driven by dispersal and habitat quality (Zhang et al., 2026). Using water quality as the sole metric could, therefore, overestimate the degree of lake restoration (Sairike et al., 2026). A multi-faceted approach to assess the full extent of recovery is therefore necessary to identify the apparent 'last to recover' aspect, leading to more evidence-based management strategies.

Research Objective

The objectives are to: (1) establish a multi-indicator ecological recovery index for assessing recovery in lakes polluted by different mechanisms, (2) quantify indicators for recovery of physicochemical, sediment, biological, and functional characteristics, (3) establish a normalized and weighted CERI, (4) compare the degree of ecological recovery for different restoration scenarios, and (5) determine the indicators that are most strongly related to recovery and restoration priority. These objectives tightly integrate indicator measurement, index building, and management interpretation into a single workflow.

Research Contributions

This study advances four contributions. First, it develops a comprehensive four-dimensional ecological recovery assessment framework. Second, it offers a transparent, comparable composite index, the CERI, to assess the recovery status of lakes. Third, it tests a multidimensional assessment of rehabilitation that distinguishes water quality improvement from sediment, biological, and functional recovery. Fourth, it introduces a decision-support method to guide lake management priorities. These elements are also articulated in ways that allow them to be replicated based on observed, measured monitoring data. Each of these elements is capable of being built upon to facilitate assessment and management of recovering lakes.

The paper is divided into six sections. Section 1 introduces the problem of lake pollution, research objectives, and scientific contributions. Section 2 summarizes current approaches to ecological assessment and research gaps. Section 3 describes the multi-indicator approach used in this study and the development of CERI. Section 4 synthesizes demonstration results. Section 5 discusses ecological recovery, management implications, and limitations. Section 6 concludes this study and future validation needs.

II. Literature Review

Ecological Impacts of Lake Pollution

Nutrient loading results in eutrophication, with algal blooms, oxygen depletion, and dominance by tolerant species (Tang et al., 2024). External loadings provide excess phosphorus and nitrogen to support these conditions, but the internal loading that occurs when the external input stops can maintain them for months or years (Zhang et al., 2026). Toxic metals contaminating the food web and affecting metabolism, reproduction, and growth cause additional physiological stress. These combined effects of oxygen deficiency and chemical toxicity lead to a reduction in species diversity and simplified community composition, leaving lake ecosystems more vulnerable to additional stress and it is therefore important to identify indicators that will reflect recovery.

Lake Recovery Related Physicochemical Indicators

The five most common recovery indicators, reported by more than 90% of the studies in the EPA report, are dissolved oxygen, pH, biochemical oxygen demand, total nitrogen, total phosphorus, and turbidity. PH and dissolved oxygen reflect organic loading and metabolic load, while total nitrogen and total phosphorus convey information on nutrients and trophic status (Liu et al., 2024). Turbidity provides information on suspended solids and algal biomass, thereby constraining light availability. These parameters are rapidly and cost-effectively measured with loads; however, these factors characterize water quality, not organism or habitat response.

Sediment Quality & Contamination Analysis

Benthic sediments are long-term sinks for metals, nutrients and organic contaminants. Lead, cadmium, and copper adsorb onto particles and organic matter, thus persisting in the environment for decades after they are no longer being deposited (Zhou et al., 2025). Ecological risk indices compare contamination to background levels; sediment organic carbon affects how pollutants are adsorbed and oxygen demand. Contaminated sediments can release nutrients and metals into the water column; thus, the state of the

sediment has a strong influence on the sustainability of water quality improvements once a site has been restored. Sediment measures complement those of water and can uncover otherwise hidden pollution legacies.

Biological Indicators of Ecosystem Condition

Phytoplankton and zooplankton provide rapid responses to nutrients and predation, whereas benthic macroinvertebrates reflect integrated periods of time and comprise taxa sensitive to pollution. Diversity metrics (e.g., the Shannon index), together with native species richness, give a concise summary of community composition and recolonization status. Biological indicators synthesize the influence of numerous stressors and are the direct target of restoration, yet they are seasonal and recover later than chemistry. They are thus vital for confirming chemical recovery is not artifactual (Jiang et al., 2025). More taxonomic groups enhance robustness of biological assessment.

Integrated Ecological Assessment Approaches

Indexing the state of lakes: water-quality index, synthesized from physico-chemical variables; trophic-state index, based on nutrients and chlorophyll-a; biological integrity index, based on biological community comparisons with reference sites; multicriteria index, integrating various indicators by normalization and weighting (Liu et al., 2024; Liu et al., 2025). These approaches represent only a fraction of lake condition, and most do not synthesize sediment, biological, and functional evidence with variation over time into a single measure relative to reference sites (Miao et al., 2025). All of these indices fall short of describing lake recovery as a multidimensional process with a temporal dimension.

Literature Summary and Gap Detected

Physicochemical, sediment, and biological indicators are related and provide complementary information, but they differ in their sensitivity over time. Few indices include all of them, normalize reference values and contemporary states, and usually focus on only one time point. There is a need for a composite recovery index using multiple ecological state factors, temporality, and reference values. The proposed framework converts various different indicators into comparable values and combines them in a transparent way in the CERI.

III. Materials and Methods

Study Design and Lake Selection

The framework was illustrated based on four lakes comprising a pollution/restoration gradient. L1 is a severely polluted lake, a result of no major restoration. L2 is a moderately polluted lake, a result of partial restoration. L3 is a historically polluted lake, a result of active restoration. L4 is a relatively pristine reference lake (all values are hypothetical; the values reported here are a dataset that should be replaced with measured data). A field application should report lake locations, surface areas, depths, land use in its watershed, pollution sources, restoration history, and other relevant history.

Water and Sediment Sampling

The design schedule is 12 months, with monthly samples at 3 stations per lake. Water samples are taken from the surface and, if possible, from near the bottom, while the surface sediment (0- 5 cm) is sampled at each station. Biological surveys are undertaken quarterly. Reference conditions are defined from L4 and, if available, state or national historical or regional reference information. The schedule attempts to provide information throughout all seasons, quality control measures incorporated include field blanks, duplicate samples, use of calibrated equipment and certified reference materials for metals analysis. Analysis is performed using conventional methods for water and sediment examination.

Selection of Ecological Recovery Indicators

They include 4 dimensions shown in table 1 show Physicochemical indicators for improvement of water quality, sediment indicators for contamination levels and sediment condition, biological indicators for recovery of communities, and functional indicators for states of the ecosystem. Chlorophyll-a and nutrient retention should be compared to reference values for each lake as higher values are not necessarily better. Indicators were selected on the basis of being ecologically meaningful and sensitive to restoration, practically measurable and available for each lake from monitoring data. Functional indicators include chlorophyll-a, metabolism balance, and nutrient retention; sediment indicators include Pb, Cd, Cu, and sediment organic carbon (see text for details).

Table 1: Selected Indicators for Multi-Dimensional Ecological Recovery Assessment

Dimension	Selected indicators	Ecological relevance
Physicochemical	DO, BOD, TN, TP, turbidity	Water quality improvement
Sediment	Pb, Cd, Cu, sediment organic carbon	Contamination and sediment condition
Biological	Shannon diversity, macroinvertebrate index, native species richness	Biological community recovery
Functional	Chlorophyll-a, metabolism balance, nutrient retention	Ecosystem functional recovery

Indicator Normalization

All indicators are normalized to a common 0-1 scale. Equation (1) is used when high values are indicative of good condition, and the inverse equation (2) when low values are better. N_i is the normalized score, X_i is the observed value, and X_{min} and X_{max} are the ecological assessment limits as defined. Values are truncated to the range [0,1]. For indicators that have an ecological optimum rather than a monotonic relationship, a suitability function was used in place of the linear normalization equations. The translation of values to a common scale permits the combination of different measures with different units into a common domain.

$$N_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (1)$$

$$N_i = \frac{X_{max} - X_i}{X_{max} - X_{min}} \quad (2)$$

CERI Development

The composite index value CERI is the weighted sum of the four-dimension scores in equation (4), where the weights have the subscript j and sum to 1; for demonstration, we use equal weights of 0.25 so as not to impose assumptions about the relative importance of dimensions. Each dimension score D_j is the average of the n_j normalized indicators for that dimension, as in equation (3). The index is transformed to a scale of 0-100 using equation (5). Dimension scores are preserved for diagnosis.

$$D_j = \frac{1}{n_j}\sum_{k=1}^{n_j} N_{jk} \quad (3)$$

$$CERI = \sum_{j=1}^{4} w_j D_j, \ \sum_{j=1}^{4} w_j = 1 \quad (4)$$

$$CERI_{100} = 100 \times CERI \quad (5)$$

Ecological Recovery Classification

Recovery is categorized into five operational CERI intervals: very poor, 0-20; poor, 20-40; moderate, 40-60; good, 60-80; and high, 80-100. Scores on a boundary are classed into the higher class. The thresholds are operational suggestion values and need to be ecologically calibrated before use in actual lakes. Classification transforms the continuous index into classes that can be readily understood by managers, but

the dimension scores are available for diagnosis of the limiting recovery components. In the demonstration, the lakes from very poor to high classes are L1, L2, L3 and L4, respectively.

Proposed Multi-Indicator Evaluation Framework

Figure 1 depicts the proposed assessment workflow. Selecting lakes and environmental monitoring involve both polluted lakes and reference conditions. Physicochemical, sediment, biological, and functional indicators are considered simultaneously and are then carried through normalization and weighting to generate the CERI. Recovery classification and temporal assessment are then conducted before the results inform prioritization of restoration and lake management. This step-by-step approach ensures transparency at each stage and enables experimentation with different choices of normalization or weighting without altering the monitoring protocol. The proposed workflow could be used by any lake monitoring program with similar indicators.

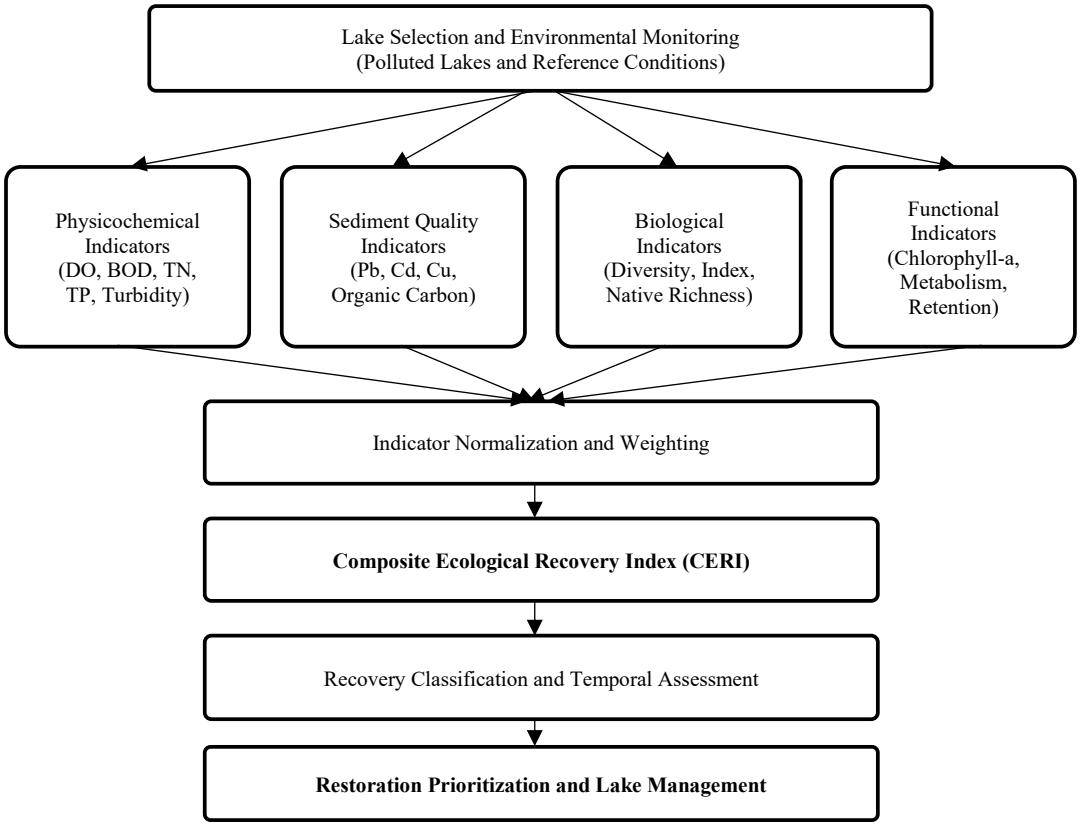


Figure 1: Proposed Multi-Indicator Ecological Recovery Assessment Framework

Statistical Analysis

Statistical analysis involves methods such as descriptive statistics, repeated-measures/mixed-effects models for temporal differences, and correlation analysis for index-interdimensional relationships. Sensitivity analysis refines the CERI by redetermining it with these alternative weights, and bootstrap confidence interval estimates reflect the uncertainty in the index. Lake rankings' sensitivity to alternative normalization procedures and weights is also tested. Statistical significance ($\alpha = 0.05$) is determined using pairwise tests, performed only after testing the data for normality and homogeneity of variance. Analyses are run using the statistical program R or Python, with all scripts, normalization limits, and weights recorded for full reproducibility of the entire analysis.

IV. Results

Physicochemical Water Quality Characteristics

Table 2 summarizes the physicochemical characteristics of each lake. Of the lakes, L1 is the most degraded, with dissolved oxygen at 2.8 mg/L, BOD at 9.2 mg/L, and high nutrient concentrations. Conditions are significantly improved in L3, with dissolved oxygen at 6.3 mg/L and BOD at 3.1 mg/L. L4 is the reference lake, with the lowest concentrations of nutrients and the highest level of dissolved oxygen. While these reflect varying degrees of pollution, they do not necessarily indicate an ecological recovery. Measures of turbidity, TN, and TP decrease from L1 to L4, but there is little variation in pH among the lakes.

Table 2: Physicochemical Characteristics of the Four Study Lakes

Parameter	L1	L2	L3	L4
DO (mg/L)	2.8	4.5	6.3	7.5
BOD (mg/L)	9.2	6.4	3.1	1.8
TN (mg/L)	3.80	2.60	1.40	0.65
TP (mg/L)	0.42	0.28	0.12	0.05
Turbidity (NTU)	42	29	15	8
pH	7.8	7.6	7.4	7.3

Multi-Dimensional Ecological Recovery Assessment

Table 3 shows the normalized scores for the three dimensions and the CERI calculated by equations (4) and (5). L1 scores lowest in all dimensions and hence the lowest CERI (18.75). L4 is highest in all dimensions, receiving a CERI of 93.50. L3 scores good (72.75) in all dimension. Its sediment score (0.69) is lower than its physicochemical score (0.76), revealing that even with better water quality, consequences of residual sediment impairment can last. Functional and biological scores are on the same gradient, so all four dimensions show consistent signals of recovery. The overall, composite score offers more comprehensive interpretation than either individual indicator group.

Table 3: Normalized Ecological Dimension Scores and Composite Recovery Index

Assessment component	L1	L2	L3	L4
Physicochemical score	0.22	0.48	0.76	0.94
Sediment score	0.18	0.41	0.69	0.91
Biological score	0.15	0.38	0.72	0.96
Functional score	0.20	0.44	0.74	0.93
CERI (0–100)	18.75	42.75	72.75	93.50
Classification	Very poor	Moderate	Good	High

Comparison of Ecological Recovery Across Lakes

Figure 2 shows the CERI for each of the four lakes. For the CERI the lowest recovery is L1 with 18.75 and the highest is L4 with 93.50. 54 points in the index between L1 and L3 is an indication that the index can discriminate between different levels of recovery with the index qualities being 0. Very poor, 1. Moderate, 2. Good and 3. High. The intermediate lakes L2 and L3 sit at levels between the extremes. The values were designed to give contrasting values and do not constitute validated index qualities which would need to be derived from measured data from the lakes.

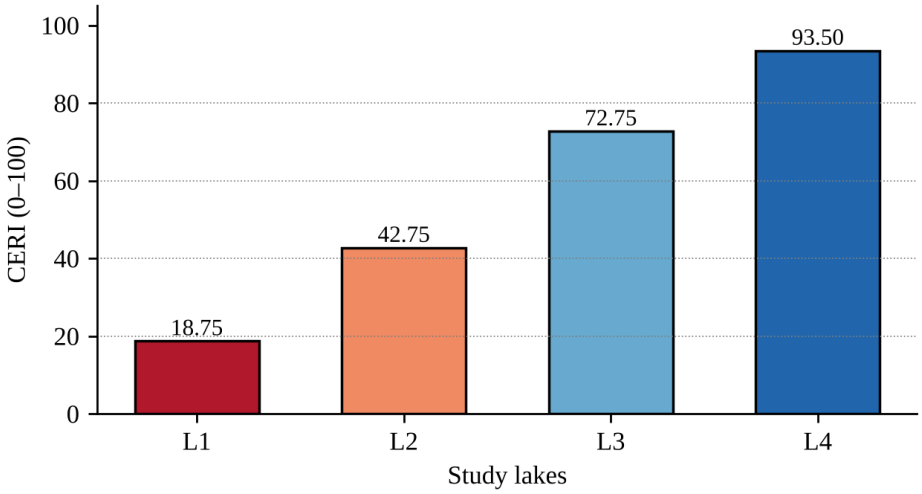


Figure 2: CERI Across the Study Lakes

Temporal Changes in Ecological Recovery

Figure 3 shows the quarterly trajectories of CERI. L3 rises from 51.40 in Q1 to 72.75 in Q4 (an increase of 21.35 index points). L2 rises by 7.15 index points, whereas L1 is essentially unchanged, increasing by 1.55 index points. L4 has remained consistently close to the reference condition. The patterns of increasing L3 and L2 and stagnant L1 patterns illustrate how successive monitoring can distinguish otherwise similar dynamics of long-term restoration and no improvement. Had monitoring been seasonally controlled and formal statistical tests been employed (e.g. Mixed-effects models of 3.8), true recovery, partial recovery, or no recovery could have been asserted from these examples.

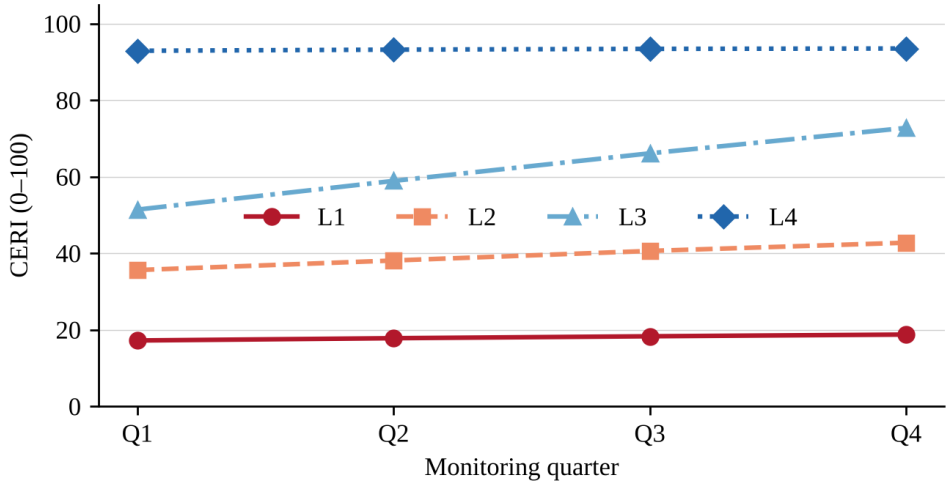


Figure 3: Quarterly CERI Trajectories of the Study Lakes; Q4 Values Match Table 3

Indicator Sensitivity and Recovery Priorities

Table 4 recalculates the CERI for expert and sediment-emphasized weights (Table 2), with scores changing less than one point, lake ranks unchanged, and class boundaries remaining the same; the framework was robust in this dataset, suggesting that managers could focus on sediment remediation and biological monitoring in L3 without losing consistency in routine surveillance.

Table 4: CERI (0–100) Under Alternative Weighting Schemes (Physicochemical, Sediment, Biological, Functional)

Weighting scheme	L1	L2	L3	L4
Equal (0.25 each)	18.75	42.75	72.75	93.50
Expert (0.30, 0.25, 0.25, 0.20)	18.85	42.95	72.85	93.55
Sediment-emphasized (0.20, 0.40, 0.20, 0.20)	18.60	42.40	72.00	93.00
Classification (all schemes)	Very poor	Moderate	Good	High

V. Discussion

The forthcoming CERI is a multi-indicator index used to evaluate lake restoration using physicochemical, sediment, biological and functional indicators. Unlike traditional water quality indices, CERI integrates information on differences in ecological recovery trajectories and sensitivities to residual impairments. In the example of four lakes, information from indices and biological conditions indicates four specific restoration scenarios, ranging from lack of lake restoration (L4), gradual recovery of the actively restored lake L3 (C4), and attainment of the long-term restored state of the lake L4 (C4). Sediment contamination coupled with lag in biological recolonization is identified as a major contributing factor to residual impairments. Comparing the CERI index with common water quality and trophic-state indices shows a more comprehensive ecological interpretation and transparent scoring of index scores. CERI can be used as a research tool to inform restoration decisions, adaptive management, and environmental policy decisions. The application of the framework to individual lakes can be influenced by reference-site selection, indicator sample size, indicator weighting, seasonality, and discrepancies between scoring ranges and standardized indexes. Validation of index performance, development of ecologically relevant threshold levels, quantification of uncertainty, and application to natural and managed ecosystems are recommended for future work.

VI. Conclusion

In this study, a MIAF was constructed for evaluation of ecological recovery of polluted lakes. Integration of multiple ecological domains (i.e., physicochemical water quality, sediment quality, biological integrity, and ecosystem functioning) resulted in a single CERI showing the overall score and condition of the lake. The framework serves as a comprehensive assessment system for evaluating the recovery condition, identifying residual ecological impairments, and comparing the recovery conditions among lakes. Performance of the combined MIAF in the synthetic demonstration is illustrated in the 4 lakes, with a CERI score for heavily polluted lake (18.75) and the reference lake (93.50), and a CERI of the actively restored lake (72.75) indicating good condition; an average score of 21.35 points was gained in the actively restored lake. Further study based on quarterly assessment showed that the actively restored lake improved by 21.35 points in the CERI score, reflecting the temporal change between different lakes. Potential ecological constraints of sediment contamination and lagged biological recovery occurred despite improvement of physicochemical water quality. As a multi-indicator framework, the integrated approach could assess broader conditions than conventional water quality-based systems. Sensitivity analysis indicated a stable ranking of lakes with an alternative weight scheme, suggesting the validity of the demonstration. Nevertheless, the synthetic demonstration based on synthetic values did not allow to prove the actual restoration efficacy, to reveal the impact of seasonal variation, and to quantify uncertainties. Future research should include field measurements, examination of ecological classification thresholds, consideration of seasonal variation across different freshwater ecosystems, and quantification of uncertainty. This study introduced a transparent and flexible ecological assessment framework to support strategic assessment, restoration prioritization, long-term monitoring, evidence-based management and sustainable conservation of freshwater lakes.

References

[1] Dong, B., Qin, B., Zhou, Y., & Shi, K. (2025). Long-term spatial and temporal dynamics of ecosystem health in Lake Taihu: Insights from multi-scale field observations and holistic assessments. *Ecological Indicators*, *181*, 114414. https://doi.org/10.1016/j.ecolind.2025.114414

[2] Weng, X., Gao, D., Tian, X., Zeng, T., Shi, H., Zhang, W., Guo, M., Su, R., & Zeng, H. (2025). Regionalized Assessment of Urban Lake Ecosystem Health in China: A Novel Framework Integrating Hybrid Weighting and Adaptive Indicators. *Sustainability*, *17*(24), 11381. https://doi.org/10.3390/su172411381

[3] Zhang, Y., Jia, S., & Li, R. (2026). Study on the Health Assessment of Rivers and Lakes on the Qinghai Plateau Based on an AHP–TOPSIS Model. *Sustainability*, *18*(1), 79. https://doi.org/10.3390/su18010079

[4] Miao, L., Zhou, H., Adyel, T. M., Chen, Y., Kong, M., You, G., Wu, J., & Hou, J. (2025). Assessment of riverine water ecological health from multi-indicator and land use perspectives. *Process Safety and Environmental Protection*, *199*, 107341. https://doi.org/10.1016/j.psep.2025.107341

[5] Tang, S., Yang, H., & Li, Y. (2024). Environmental Assessment and Restoration of the Hunjiang River Basin Based on the DPSIR Framework. *Sustainability*, *16*(19), 8661. https://doi.org/10.3390/su16198661

[6] Liu, Y., Mu, Z., Dong, W., Huang, Q., Chai, F., & Fan, J. (2024). Establishment of an evaluation indicator system and evaluation criteria for the Weihe River ecological watersheds. *Water*, *16*(17), 2393. https://doi.org/10.3390/w16172393

[7] Zhou, Y., Li, C., & Yang, W. (2025). Dynamic assessment of the eco-environmental effects of open-pit mining: A case study in a coal mining area (Inner Mongolia, western China). *Sustainability*, *17*(11), 5078. https://doi.org/10.3390/su17115078

[8] Jiang, Y., Li, H., Zhang, Z., Ren, G., & Zhang, J. (2025). Enhancing ecological sustainability in ion-adsorption rare earth mining areas: A multi-scale model for assessing spatiotemporal dynamics and ecological resilience. *Ecological Modelling*, *502*, 111038. https://doi.org/10.1016/j.ecolmodel.2025.111038

[9] Liu, T., Zhang, Y., Liu, Y., & Chen, B. (2025). Multi-indicator assessment of heavy metal pollution in Qinzhou Harbour sediments: Unraveling ecological and human health risks. *Marine Pollution Bulletin*, *211*, 117442. https://doi.org/10.1016/j.marpolbul.2024.117442

[10] Sairike, A., Kawano, N., Vasileva, V. B., & Chen, M. (2026). Ecological Monitoring of Nuclear Test Sites over 20 Years Based on Remote Sensing Ecological Index: A Case Study of the Semipalatinsk Test Site. *Sustainability*, *18*(1), 206. https://doi.org/10.3390/su18010206