

Research Progress and Prospects of Aquatic Ecological Assessment

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Abstract

Aquatic ecological assessment serves as the core technical support for the transition of watershed water environmental management from water quality target-oriented to ecological health target-oriented. Based on representative Chinese and English literature indexed in CNKI and other databases over the past four decades, this paper systematically reviews the conceptual connotation, theoretical basis, indicator system and methodological evolution of aquatic ecological assessment. The review shows that mature research paradigms have been established internationally, represented by the Index of Biotic Integrity (IBI) and Rapid Bioassessment Protocols of the United States[1], ecological status assessment under the EU Water Framework Directive (WFD)[2], and the Australian River Assessment System (AUSRIVAS). In China, aquatic ecological assessment has evolved from physicochemical water quality assessment and single-discipline biological assessment toward comprehensive multi-factor assessment integrating physical, chemical and biological components[3]. A national standard system has been preliminarily established, represented by GB/T 43476—2023 Technical Guidelines for Aquatic Ecological Health Assessment[4]. At the current stage, several bottlenecks remain, including inconsistent methodologies and poor comparability of assessment results in reference condition determination, aquatic ecoregionalization, indicator weighting, and stressor identification. Future efforts should prioritize the integration of emerging monitoring techniques such as environmental DNA (eDNA) with conventional approaches, develop machine learning-assisted comprehensive diagnostic methods using multi-source data, and accelerate the construction of a closed-loop technical framework covering assessment–diagnosis–restoration.

Keywords

Aquatic Ecological Assessment; Ecosystem Integrity; Aquatic Ecological Assessment Indicator System

1. Introduction

Aquatic ecosystems underpin biodiversity conservation, water resource provision and ecological security in river basins. Accelerated industrialization and

urbanization have superimposed multiple stressors including nutrient enrichment, habitat fragmentation and homogenized hydrological regimes. Conventional water quality assessment centered on chemical indicators can hardly reflect the actual structural and functional status of aquatic ecosystems[3]. Against this backdrop, aquatic ecological assessment, as a technical tool to quantify ecosystem health and identify key stressors, has become a central component of water environment management and ecological restoration decision-making.

Globally, an academic theoretical framework centered on ecological integrity has been developed for aquatic ecological assessment[5]. The EU, United States, Australia and other jurisdictions have built regionally adapted assessment frameworks[2,6]. Since the Index of Biotic Integrity (IBI) and other methods were introduced into China in the early 21st century, notable progress has been achieved in indicator system development, watershed-scale application and standardization[3,4]. Nevertheless, the field remains in an exploratory phase with prominent challenges such as inconsistent theoretical foundations, non-standardized assessment protocols, and low comparability of evaluation outcomes[7].

This study targets representative Chinese and English papers published from 1985 to 2025, retrieved from CNKI and other databases. A total of 1557 publications were obtained, among which 970 are Chinese articles and 311 are English articles. Three screening principles were adopted:

- (1) priority to highly cited original research and methodological reviews in authoritative journals such as *Journal of Lake Sciences* and *Environmental Science*;
- (2) inclusion of foundational documents for mainstream international assessment frameworks;
- (3) coverage of normative documents including national standards and technical guidelines.

By systematically synthesizing existing findings, this paper summarizes the connotation and theoretical basis of aquatic ecological assessment, characterizes its indicator systems and methodologies, identifies current limitations and discusses prospects for future research directions, aiming to provide references for establishing an aquatic ecological assessment framework suited to China's national conditions.

2. Connotation and Theoretical Basis of Aquatic Ecological Assessment

2.1. Evolution of Conceptual Connotation

The concept of aquatic ecological assessment has been continuously enriched alongside shifts in water environmental management philosophy. Early assessments relied primarily on physical and chemical indicators to characterize pollution levels and water use functions. In the 1980s, Karr (1981) proposed the concept of biotic

integrity, defined as “the capacity of a balanced, adaptive biotic community to support and maintain a species composition, diversity and functional organization consistent with the natural habitat of a region”. This milestone expanded assessment objects from physicochemical water properties to biological community structure. Since the 21st century, parallel concepts including ecosystem health, ecological integrity and ecological status have been developed. Kuehne et al. (2017) noted that ecological integrity assessment has expanded from single biotic groups toward multi-trophic comprehensive evaluation. Chinese scholars further put forward the concept of aquatic ecological health, emphasizing multi-factor comprehensive criteria centered on aquatic biota and integrated with physical habitat and chemical water quality[3,8].

2.2. Theoretical Basis

(1) Biota–environment relationship theory

The biota–environment relationship constitutes the fundamental theory for aquatic ecological assessment. Niche theory and metacommunity theory play critical roles in the evolution of assessment frameworks, indicator optimization and performance improvement[8], providing a basis for inferring environmental stress through biological community responses.

(2) Ecosystem integrity theory

Yi Yujun et al. systematically reviewed the evolution of aquatic ecological health connotation and argued that indicator systems based on ecological integrity exhibit advantages in classification, workflow and operability. This theory highlights multi-dimensional characterization of ecosystem status from structure, function and ecological processes.

(3) Pressure–State–Response (PSR) framework

Most technical specifications adopt the PSR model for indicator screening logic, requiring core indicators to respond significantly along environmental stress gradients to guarantee the sensitivity of assessment results to anthropogenic disturbances[9].

3. Indicator Systems for Aquatic Ecological Assessment

Indicator systems are the core of aquatic ecological assessment[3,10]. Current research widely adopts a three-component framework: physical habitat – physicochemical water quality – aquatic biota. The three components characterize habitat conditions, pollution pressure and biological responses respectively, forming a holistic depiction of ecosystem status[4].

(1) Physical habitat indicators

Physical habitat indicators reflect hydrological processes, spatial connectivity and riparian habitat conditions, mainly including ecological water requirement satisfaction index, flow variability index, water network connectivity index, riparian

disturbance index, habitat disturbance index, etc. Liu Huan et al. proposed regional and typological thresholds of river ecological baseflow proportion based on 439 national hydrological sections, supporting the quantification of hydrological indicators.

(2) Physicochemical water quality indicators

Physicochemical indicators reflect water self-purification capacity, trophic state and pollution risk. Common parameters include dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), chlorophyll-a, etc. Widely adopted assessment methods comprise single-factor evaluation, comprehensive pollution index, trophic state index and water quality index[3,7].

(3) Aquatic biological indicators

Biological indicators are the core of aquatic ecological assessment, reflecting the integrity of ecosystem structure and function[1,10]. Common biotic groups and metrics include diversity indices, organism density and dominance of phytoplankton and zooplankton, which are mainly applied in lake eutrophication assessment. The integrity indices of benthic macroinvertebrates, periphytic algae and fish are designated as core biotic integrity parameters in GB/T 43476—2023.

4. Existing Problems and Future Prospects

4.1. Main Challenges

Despite substantial advances in aquatic ecological assessment, the following issues restrict further development.

(1) Lack of unified methods for reference condition determination. Reference sites act as the “benchmark” for assessment. However, undisturbed reference sites are rarely available in heavily impacted watersheds[2]. Current approaches include best attainable condition, historical data reconstruction and model prediction, yet outputs differ substantially, directly undermining the accuracy of assessment results[5,10].

(2) Incomplete aquatic ecoregionalization system. China covers a vast territory with marked natural gradients. Previous studies have attempted to build a national aquatic ecoregional system of primary and secondary zones (four primary zones: Eastern, Central, Northwest and Southwest China; 34 secondary zones) based on the Gini coefficient, while the linkage between ecoregional indicators and assessment systems remains to be strengthened.

(3) Insufficient standardization of indicator systems and assessment methods. Divergences in indicator selection, sampling protocols and weight assignment across domestic studies lead to poor spatial and temporal comparability of assessment results.

(4) Insufficient transition from “status assessment” to causal diagnosis. Composite indices can reflect overall health status, yet management decisions require identification of key stressors and their transformation pathways. Stressor

diagnostic tools (e.g., US EPA Stressor Identification and CADDIS) have not been widely applied in China.

(5) Inadequate integration of novel monitoring technologies. eDNA technology features high sensitivity, non-invasiveness and capacity to cover multiple biotic groups, but challenges persist regarding quantitative precision, standardized workflows and compatibility with conventional sampling methods[11].

4.2. Future Prospects

(1) Establish a closed-loop “assessment–diagnosis–restoration” system. Promote diagnostic assessment that quantifies ecological status and identifies stressors as the mainstream paradigm, ensuring assessment outputs directly support ecological restoration decision-making.

(2) Integrate multi-technologies and develop digital and intelligent monitoring. Combine eDNA with remote sensing, automatic monitoring and big data analytics to shift from discrete point sampling toward watershed-scale dynamic perception. Multi-trophic eDNA-based composite biotic integrity indices are more sensitive to ecological degradation than single-group metrics and represent a key research direction[11].

(3) Refine aquatic ecoregionalization and reference condition systems. Construct refined aquatic ecoregions incorporating climate, hydrology, geomorphology and biogeographic factors, and define region-specific reference conditions and assessment benchmarks to improve cross-region comparability.

(4) Adopt intelligent approaches such as machine learning. Statistical approaches including principal component analysis, random forest and Bayesian networks show advantages in multi-indicator comprehensive assessment and stressor identification, compensating for the limitations of classical statistical methods.

(5) Strengthen alignment with national management demands. Against the policy backdrop of Beautiful Rivers and Lakes construction and aquatic ecological performance assessment, accelerate the development of monitoring systems aligned with Essential Biodiversity Variables (EBVs), and fill monitoring gaps at genetic diversity and ecosystem function levels.

5. Conclusions

Aquatic ecological assessment has evolved from single-item water quality evaluation centered on chemical metrics to diagnostic comprehensive assessment dominated by biotic integrity and integrating physical, chemical and biological components. Internationally mature paradigms have been formed, represented by IBI, WFD and AUSRIVAS. Drawing on international experience, China has preliminarily built its national standard system. Future research should address critical bottlenecks including reference condition determination, aquatic ecoregionalization and methodological standardization, facilitate the integrated

application of novel technologies such as eDNA and machine learning, and accelerate the development of an integrated “assessment–diagnosis–restoration” technical system, providing scientific support for watershed aquatic ecological conservation and restoration[12-13].

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