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Original Paper

Research on River Ecosystem Restoration and Sustainable Governance Strategies Based on Ecological Isotope Technology

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Abstract

Degradation of river ecosystems is a global water environment problem. Traditional engineering governance models focus on flood control and river channel regulation, while ignoring the systematic restoration of ecological functions. Based on ecological isotope tracing technology, this article systematically studies the impact mechanism of river morphological changes, water flow velocity distribution and river bed stability on the ecosystem, and builds a three-in-one governance framework of "hydrodynamic simulation-isotope tracing-ecological restoration strategy". Research shows that stable isotopes of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$) can effectively trace material circulation and energy flow paths in river ecosystems, quantify the impact of hydrological connectivity on food web structure, and provide precise targeting for active ecological restoration. This article proposes to improve the hydraulic model to enhance the unsteady and nonlinear prediction capabilities, and combine isotope monitoring data to optimize restoration timing and program selection, providing theoretical support and practical paths for the transformation of river engineering management from "single engineering orientation" to "ecological collaborative management".

Keywords

ecological isotopes, river ecosystem, hydrodynamics, ecological restoration, sustainable governance

1. Research Background and Significance

With the intensification of human activities and the impact of climate change, global river ecosystems are facing multiple pressures such as changes in hydrological regimes, decline in biodiversity, and degradation of water quality. Problems such as over-construction of gates and dams, hardening of river channels, and insufficient ecological flow are common in major rivers in my country. The traditional management model focuses on engineering measures, emphasizing flood control safety and water supply, and paying insufficient attention to the self-purification capacity, habitat function, and food web structure of the river ecosystem. In recent years, although various regions have continued to promote the construction of happy rivers and lakes and ecological restoration projects, the evaluation of restoration effects has mostly stayed at the level of water quality indicators, lacking a quantitative understanding of the intrinsic connectivity and material recycling efficiency of the ecosystem.

By analyzing the natural abundance changes of stable isotopes in water and organisms, ecological isotope technology can reveal hydrological processes, nutrient sources and food web dynamics, and provide a technological leap from "appearance monitoring" to "mechanism diagnosis" for river ecological restoration. Combining isotope tracing with river dynamics simulation can help accurately identify key links in ecological degradation and formulate restoration strategies based on ecosystem integrity. It has important theoretical and practical value in promoting river management from passive response to active restoration.

2. Degradation Characteristics and Governance Dilemmas of River Ecosystems

2.1 River Morphological Changes and Ecological Response

Changes in river morphology are the direct driving force of ecological degradation. Engineering interventions such as cutting and straightening river channels, regularizing cross-sections, and hardening bank slopes change the distribution of water flow velocity and the pattern of erosion and siltation of the river bed. Research shows that asymmetrical channel widening and narrowing will change the distribution of cross-section flow velocity peaks, and the erosion and sedimentation characteristics of the river bed cross-section depend on the flow velocity changes during the flood process and the critical starting flow velocity of the bed sand. Erosion will increase the stability of hydrodynamic conditions, but the evolving shape of the river bed does not simply change with the flow rate. This change in hydrodynamic conditions directly affects the availability and stability of benthic habitats, thereby reconstructing the energy basis of the food web.

2.2 Ecological Consequences of Loss of Hydrological Connectivity

The construction of gates and dams and river channelization have resulted in a significant decrease in the longitudinal, transverse and vertical connectivity of the river. The loss of connectivity blocks the migration and exchange of nutrients, organic matter and organisms, which is one of the core mechanisms of river ecological degradation. Isotope tracing studies show that hydrological connectivity dominates nitrogen cycling processes in complex landscapes. In the case of the Danube River side branch system, the side branch system is dominated by self-sourced organic matter at low water levels, and river organic matter becomes the dominant source at high water levels. At medium connectivity levels, the side branch system is still dominated by self-sourced organic matter and can export bioavailable organic matter to the main river. This finding shows that maintaining moderate hydrological connectivity is not only a requirement for hydrological processes, but also a guarantee for the functional integrity of the ecosystem.

2.3 Limitations of Traditional Governance Models

At present, the main goal of river management is "flood control safety + water quality compliance", and engineering measures focus on embankment construction, dredging, and pollution interception and control. This type of model has three limitations: first, it ignores the nonlinear response characteristics of the ecosystem, and the achievement of a single indicator does not equal the health of the ecosystem; second, the restoration effect lacks long-term tracking and mechanism evaluation, making it difficult to accumulate experience and feedback optimization; third, engineering decisions mostly rely on empirical judgment and lack the ability to quantify the ecological evolution trend after restoration. To solve the above dilemma, it is necessary to introduce new technical means that can simultaneously characterize hydrological processes and ecological functions.

3. Theoretical Basis and Technical Framework of Ecological Isotope Tracing

3.1 Core Principles of Ecological Isotope Tracing

Stable isotopes fractionate in natural processes due to differences in physical and chemical properties, and changes in their ratios can record the "fingerprint information" of material migration and transformation. In river ecosystems, $\delta^{18}O$ and δD mainly trace water sources and mixing processes, $\delta^{13}C$ reveals organic matter sources and carbon cycle paths, and $\delta^{15}N$ reflects nitrogen transformation and trophic level positions. An international research team analyzed hydrogen and oxygen stable isotopes in 136 perennial rivers and 45 large watersheds around the world and found that dynamic water retention indicators can effectively describe the speed of water flow through the watershed. Watersheds with low dynamic water retention are more susceptible to hydrological extreme events such as droughts and floods. This discovery provides a scientific basis for using isotopes to predict river hydrological risks and optimize the timing of ecological restoration.

3.2 Diagnostic Advantages of Multi-isotope Combination

Information on single isotope indicators is limited, and the combined use of carbon and nitrogen isotopes can simultaneously analyze the source of materials and the transformation process. In the study of Miyun Reservoir, the combined use of nitrogen and oxygen isotopes clarified the contribution proportion of total nitrogen to pollution sources; in the study of Liaohe River sediments, carbon and nitrogen isotope fingerprints revealed the differences in sources of organic matter in sediments of different particle sizes. The combined use of multi-isotopes makes it possible to diagnose the entire chain from "what the pollutants are" to "where the pollutants come from, where they go, and how they are transformed", providing precise targeting for the formulation of remediation strategies.

3.3 "Hydrodynamics-isotope-ecology" Coupling Framework

This paper proposes a technical framework that couples hydrodynamic numerical simulation with isotope tracer monitoring (Table 1). This framework uses a hydrodynamic model to simulate river morphological changes and water flow distribution, and uses isotope monitoring to verify material migration and ecological response. The two calibrate and complement each other, forming a closed loop of "simulation prediction-isotope verification-strategy optimization".

Table 1. Application Scenarios of Ecological Isotope Indicators in River Ecosystem Diagnosis

Isotope Indicator	Main Tracing Target	Application Scenario	Typical Reference Value Range
$\delta^{18}O$, δD	Water source and mixing ratio	Hydrogeological connectivity assessment, groundwater-surface water interaction	Global Meteoric Water Line δD=-10‰~-50‰
$\delta^{13}C$	Organic matter source (C3/C4 plants, aquatic algae)	Food web basal carbon source analysis, terrestrial-aquatic organic matter exchange	C3 plants -27‰, C4 plants -13‰
$\delta^{15}N$	Nitrogen source and transformation (denitrification, nitrogen fixation)	Pollution source apportionment, trophic level determination	Atmospheric N_2 0‰, fertilizer -3‰~+3‰
$\delta^{34}S$	Sulfate source	Acid mine drainage tracing, sulfur cycle	Significant differences among various sources

Note. The reference value range is comprehensively compiled based on the International Atomic Energy Agency (IAEA) database and Global Isotope Monitoring Network (GNIP) data.

4. Key Technical Methods and Implementation Paths

4.1 Hydraulic Model Improvement and Multi-source Data Fusion

Traditional hydraulic models are mostly based on the assumption of steady-state uniform flow, which makes it difficult to accurately describe the non-constant and non-uniform characteristics of natural rivers. This paper proposes a parameterization scheme that introduces unsteady terms and nonlinear corrections based on the existing model to improve the convection and diffusion processes, so that the model can better capture the flow changes under dynamic scenarios such as flood processes, tidal effects, and gate and dam operation. At the same time, isotope monitoring data are used as independent constraints for model calibration and verification, and model parameters are calibrated with measured isotope characteristics to improve prediction reliability.

4.2 Identification of Ecological Restoration Target Areas Based on Isotope

Repair target identification is the prerequisite for active repair. By analyzing the spatial distribution of carbon and nitrogen isotopes in different sections of the river before restoration, three types of key areas can be identified: isotope abnormal areas (indicating pollution input or sudden changes in organic matter sources), isotope gradient areas (indicating hydrological mixing or ecological transition zones), and isotope homogeneous areas (indicating that the system tends to be stable but may have a single function). The three types of areas correspond to different restoration strategies - abnormal areas require source control, gradient areas should implement connectivity restoration, and homogeneous areas should focus on habitat diversity reconstruction.

4.3 Isotope Tracking Evaluation of Repair Effect

The assessment of restoration effects should not stop at a single sampling after restoration, but should establish a long-term isotope monitoring sequence. Research by Schlenker et al. showed that the nutritional similarity of benthic food webs continued to improve after restoration and approached the natural level, but resource diversity declined within 10 years after restoration, which may be due to the resource substitution effect in the early stages of restoration. This finding suggests that the assessment of restoration effects needs to distinguish short-term disturbances from long-term trends, and that temporal changes in isotope indicators have more diagnostic value than single-point values. It is recommended to establish an isotope baseline monitoring system before restoration, during restoration, and after restoration during the planning stage of the restoration project, with a tracking period of at least 3 to 5 years.

4.4 Formulation of Sustainable Governance Strategies

Based on the above technical path, the sustainable governance strategy should include four levels: prevention layer - identify ecological degradation risk areas through isotope early warning and implement intervention before degradation is irreversible; restoration layer - select appropriate restoration technology combinations (such as ecological bank protection, water system connection, habitat reconstruction, etc.) based on isotope diagnosis results; evaluation layer - establish a multi-dimensional evaluation system of restoration effects with isotope indicators as the core; adaptation layer - dynamically adjust management measures based on tracking monitoring results, forming an adaptive management cycle of "monitoring-evaluation-adjustment".

5. Conclusion

This article systematically discusses the application path of ecological isotope technology in river ecosystem restoration and sustainable management. Research shows that carbon and nitrogen stable isotope tracing can effectively reveal river hydrological connectivity, organic matter sources and food web structure, making up for the shortcomings of traditional water quality monitoring in ecosystem function assessment. Coupling isotope monitoring with improved hydrodynamic models could enable a paradigm shift from “reactive remediation” to “proactive diagnostic remediation.” The study recommends incorporating special isotope monitoring projects into river management projects, establishing a baseline database and long-term tracking sequence before restoration, and optimizing restoration timing, target area selection, and program configuration guided by isotope indicators. Future research should further explore the deep integration method of isotope tracing and numerical simulation, develop differentiated technical systems suitable for different river types (mountainous rivers, plain rivers, urban rivers), and promote the substantial transformation of river management from a single engineering goal to the overall health goal of the ecosystem.

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