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Research on the Improvement of Water Resources Ecological Footprint Model and Its Carrying Capacity Response

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Abstract: As a core element of regional development, the assessment of water resources ecological carrying capacity is crucial for sustainable development. Traditional water resources ecological footprint models often yield biased results due to the neglect of water consumption in wastewater treatment, parameter dynamics, and spatial heterogeneity. This study improves model accuracy by introducing a water consumption correction coefficient, constructing a dynamic parameter system integrated with multi-source data, and coupling spatial analysis techniques. Taking typical regions as case studies, the research quantifies the spatio-temporal evolution of the water resources ecological footprint and reveals the response mechanisms of carrying capacity, providing theoretical support for the scientific management and control of water resources.

Keywords: Water resources; ecological footprint model; improvement; carrying capacity; response mechanism

Introduction

As a fundamental resource for human survival and development, the ecological carrying capacity of water resources is facing severe challenges. Although the traditional water resources ecological footprint model provides an important tool for assessing the impact of human activities on water resources, it suffers from issues such as simplistic parameters, insufficient consideration of water quality factors, and spatial heterogeneity. Therefore, this study is dedicated to improving the water resources ecological footprint model by introducing multi-dimensional parameters, water quality correction mechanisms, and spatial analysis methods, aiming to assess water resources carrying capacity more accurately and provide a scientific basis for water resources management and protection.

1. Literature Review and Theoretical Basis

1.1 Research Progress of Water Resources Ecological Footprint Models

(1) International research

The evolution of models shows a core trend from static to dynamic and from single-factor to multi-factor. Early static models focused on the accounting of water resource appropriation at a single point in time, making it difficult to reflect the chronological changes in resource consumption; subsequent dynamic models introduced the time dimension to achieve dynamic tracking and prediction of water resource footprints. Meanwhile, research has expanded from single-factor accounting focused only on water volume to multi-factor coupled models integrating associated elements such as land and energy, enhancing the comprehensiveness of the assessment.

(2) Domestic research

Focusing on regional applications, a case system covering different scales such as river basins and provinces has been formed, providing practical support for water resources management. However, there are obvious shortcomings, such as model applications mostly staying at the stage of copying international frameworks, lacking localized optimization for the characteristics of uneven spatio-temporal distribution of water resources in China, and a lack of connection between research conclusions and management practices.

1.2 Analysis of Limitations of Existing Models

(1) The problem of parameter simplification is prominent. Most existing models construct accounting systems only around the dimension of water volume, ignoring the impact of water quality deterioration on water availability. At the same time, they do not incorporate ecological service values such as water conservation and purification, resulting in assessment results that fail to fully reflect the true ecological pressure on water resources.

(2) Insufficient spatio-temporal resolution. Temporally, annual-scale accounting is mostly used, which cannot capture short-term fluctuations in water supply and demand such as seasonal or monthly variations. Spatially, models are limited by administrative boundaries, making it difficult to fit the basin-wide distribution characteristics of water resources, which restricts the assessment needs for cross-regional collaborative water resources management.

(3) Lack of human activity feedback mechanisms. Human intervention measures such as water-saving policies, water conservancy project construction, and agricultural planting structure adjustments, as well as the role of technological progress in improving water use efficiency, have not been fully considered, resulting in limited explanatory power and prediction accuracy for dynamic changes in water resources [1].

1.3 Theoretical Basis

(1) Ecological Economics Theory as the core support. This theory emphasizes the closed-loop nature of resource metabolism and the threshold constraints of ecological carrying capacity. It clarifies that as a key ecological resource, the development and utilization of water resources must be controlled within the carrying capacity of the ecosystem, providing a theoretical basis for the accounting boundaries and threshold settings of the water resources ecological footprint.

(2) System Dynamics Theory provides methodological support. It focuses on the coupling correlation and dynamic feedback mechanisms among multiple factors. It can effectively integrate multi-dimensional elements such as water resources, socio-economics, and human activities, making up for the lack of feedback mechanisms in existing models and providing methodological guidance for building a collaborative multi-factor assessment framework for the water resources ecological footprint.

2. Research on the Improvement of Water Resources Ecological Footprint Model

2.1 Improvement Framework Design

(1) Multi-dimensional parameter expansion

Addressing the flaws of simplified parameters in traditional models, a multi-dimensional parameter system is constructed covering water volume, water quality, ecological service functions, and virtual water trade. Based on water volume, a water quality dimension is added to characterize water resource availability, accounting for the increment of the ecological footprint caused by water quality degradation through pollutant concentrations. Quantitative indicators for ecological service function values, such as water conservation and hydrological regulation, are included to refine the ecological pressure assessment dimension. Virtual water trade parameters are added to consider the implicit flow of water resources in the trade of agricultural and industrial products between regions, achieving full-chain coverage of actual water resource appropriation.

(2) Spatio-temporal dynamic correction

In the time dimension, seasonal variation factors are introduced. Combined with the seasonal distribution differences in precipitation and runoff, the traditional annual-scale accounting is refined into quarterly-monthly dynamic accounting to accurately capture short-term supply-demand fluctuations. In the spatial dimension, administrative boundaries are bypassed by adopting a grid-based spatial analysis method, dividing assessment grids according to basin hydrological units to achieve refined spatial mapping of the water resources ecological footprint, aligning with the basin-wide distribution and management needs of water resources [2].

(3) Human activity coupling module

A new human activity impact module is added, constructing three sub-modules: policy scenarios (water-saving policies, inter-basin water transfer policies), technological progress (water-saving irrigation technology, wastewater treatment technology), and consumption patterns (resident water use structure, industrial consumption preferences). By quantifying the influence coefficients of various factors on water resource utilization efficiency and ecological carrying capacity, a dynamic feedback mechanism between human activities and the water resources ecological footprint is established.

2.2 Key Improvement Methods

(1) Construction of a water quality correction coefficient system. Based on environmental quality standards for surface water and groundwater, core pollutants such as COD and ammonia nitrogen are selected to establish the correspondence between pollutant concentration and water quality grades. The entropy weight method is used to determine the weight of each pollutant, and a comprehensive water quality correction coefficient is calculated and embedded into the traditional water volume accounting formula, achieving "volume-quality" collaborative ecological footprint accounting.

(2) Development of a virtual water flow network model. A multi-regional input-output analysis method is used to comb through industrial correlation chains between regions, quantify the virtual water flow of key industries such as agriculture, forestry, animal husbandry, fishery, and industrial manufacturing, and construct a "production-consumption" bidirectional virtual water flow network. This clearly defines the intrinsic and transferred water resource footprints of a region, making up for the lack of consideration for trade-implicit water resources in traditional models.

(3) Optimization of dynamic weight allocation methods. Abandoning the traditional fixed weight assignment method, the entropy weight method combined with machine learning algorithms (such as Random Forest) is used for dynamic weight optimization: the entropy weight method mines the information entropy of the data itself to determine the initial weights of parameters; machine learning algorithms are used to learn the dynamic change laws of the water resources ecological footprint in historical data to correct weight coefficients in real-time, enhancing the model's adaptability to complex system changes [3].

2.3 Model Validation and Comparison

(1) Case selection

A typical water-deficient basin in Northern China (such as the middle reaches of the Yellow River) is selected as a research case. This region features dominant agricultural water use, concentrated industrial water use, and frequent inter-regional water transfer. Its uneven spatio-temporal distribution of water resources and strong human intervention allow for a comprehensive test of the improved model's applicability and stability under complex scenarios. Meanwhile, a water-abundant basin in Southern China (such as the lower reaches of the Yangtze River) is selected as a control case to verify the model's universality in regions with different water resource endowments.

(2) Comparison with traditional model results

Comparisons are carried out in terms of accuracy improvement and sensitivity analysis: In terms of accuracy, using measured basin water resource data and ecological environmental monitoring data as benchmarks, the degree of alignment between the improved model's calculated ecological footprint values and actual ecological pressure is quantified to evaluate the extent of accuracy improvement. In terms of sensitivity, different parameter fluctuation scenarios are set (such as changes in water pollutant concentrations and fluctuations in virtual water trade volume) to compare the output response differences between traditional and improved models, testing the stability and anti-interference ability of the improved model and clarifying the core contribution of each improvement module.

3. Dynamic Response Mechanism of Water Resources Carrying Capacity

3.1 Carrying Capacity Quantification Method

(1) Carrying capacity assessment index system based

on the improved model. Relying on the previously improved multi-dimensional water resources ecological footprint model, a "Pressure-State-Response" three-dimensional assessment index system is constructed. Pressure indicators cover multi-dimensional ecological footprints such as water volume appropriation, water quality degradation, and virtual water trade transfer; state indicators include available water resources, ecological base flow guarantee rate, and water quality compliance rate; response indicators include water-saving efficiency, pollution control investment, and ecological restoration effectiveness, achieving a comprehensive quantitative representation of carrying capacity.

(2) Criteria for determining overloaded/sustainable status. The matching degree between "ecological footprint and carrying capacity" is used as the core criterion, and a three-level threshold is set: when the water resources ecological footprint is $\leqslant$ 0.8 times the carrying capacity, it is in a sustainable state, and water resource development is within the ecological safety range; when 0.8 times carrying capacity $<$ ecological footprint $\leqslant$ 1.2 times carrying capacity, it is in a critical state, and early warning and regulation need to be activated; when the ecological footprint $>$ 1.2 times the carrying capacity, it is in an overloaded state, indicating a risk of degradation in the water resources ecosystem, requiring strict management measures. Meanwhile, indicators such as the water quality compliance rate and the integrity of ecological service functions are integrated for collaborative judgment to enhance the scientific nature of the criteria.

3.2 Analysis Framework of Response Mechanism

(1) Natural driving factors

Focus on two core natural factors: climate change and geological conditions. Climate change affects the total endowment of water resources by influencing the spatio-temporal distribution of precipitation and evaporation, thereby affecting the baseline of carrying capacity. Geological conditions (such as aquifer permeability and topography) determine the storage and replenishment capacity of water resources, indirectly acting on carrying capacity by changing the amount of available water resources. The marginal influence coefficients of both on carrying capacity need to be quantified.

(2) Human driving factors

Covering three dimensions: population growth, industrial structure, and technical efficiency. Population growth directly increases domestic water demand, expanding ecological footprint pressure; the proportion of high-water-consuming industries in the industrial structure determines industrial water intensity, affecting the supply-demand balance of carrying capacity; the improvement of technical efficiency (such as water-saving technology and wastewater treatment and reuse technology) can reduce water consumption per unit of output and raise the upper limit of carrying capacity. A driving effect model coupled with multiple factors needs to be constructed.

(3) Policy intervention effects

Focus on analyzing the intervention mechanisms of two core policies: water-saving policies and inter-regional water transfer. Water-saving policies reduce water resource consumption through economic incentives (water price reform) and administrative constraints (water use quotas), directly alleviating ecological footprint pressure. Inter-regional water transfer enhances carrying capacity by optimizing the spatial configuration of water resources and increasing the available volume in water-deficient areas. The lag and synergistic effects of policy implementation need to be evaluated [4].

3.3 Scenario Simulation and Prediction

(1) Scenario design

Two types of core scenarios are constructed: One is the SDGs goal scenario, benchmarking the requirements related to water resource security and ecological protection in the Sustainable Development Goals, setting different goals for improving water-saving rates and pollution control rates to form three sub-scenarios: baseline, optimized, and strengthened. The other is the extreme climate scenario, covering two typical scenarios: extreme drought and extreme flooding, to simulate the impact of abnormal precipitation fluctuations on water resources carrying capacity.

(2) Dynamic response paths

Trend changes in carrying capacity under different scenarios are simulated based on a system dynamics model to identify key time points and thresholds in the evolution of carrying capacity. The interaction paths of natural, human, and policy factors are clarified, and the contribution of each factor to changes in carrying capacity is determined. Differentiated response strategies are proposed for different scenarios to provide dynamic regulation plans for sustainable water resources management.

4. Policy Recommendations and Outlook

4.1 Management Strategies Based on the Response Mechanism

(1) Spatially differentiated regulation

Based on the spatial distribution characteristics of the dynamic response of water resources carrying capacity, implement zonation and classification management strategies. For water-overloaded areas, establish ecological compensation mechanisms, promote the transfer of high-water-consuming industries, and guide ecological restoration. In water-surplus areas, explore water rights trading markets, promote the cross-regional optimal configuration of water resources, and enhance overall utilization efficiency, achieving collaborative spatial management that "compensates for shortages with surpluses".

(2) Dynamic adaptive management

Relying on dynamic monitoring data of carrying capacity, construct a multi-level early warning mechanism, classifying levels into safety, warning, and crisis, corresponding to the activation of differentiated regulation measures. Meanwhile, promote a flexible planning model. Combined with dynamic factors such as climate change and industrial upgrading, periodically revise water resource utilization plans, and embed the response mechanism into the entire process of plan formulation, implementation, and evaluation to enhance the flexibility and foresight of management.

4.2 Research Deficiencies and Future Directions

(1) Data accuracy improvement.

Current research data suffers from insufficient spatio-temporal granularity and difficulties in accurately quantifying certain parameters. In the future, the application of Internet of Things (IoT) monitoring technology should be strengthened to build a real-time monitoring network covering water volume, water quality, and ecological service functions, achieving accurate data collection and dynamic updates. Meanwhile, promote the construction of cross-departmental data sharing platforms to integrate data from multiple fields such as hydrology, environmental protection, and agriculture, providing data support for model optimization.

(2) Interdisciplinary integration.

Existing research is mostly limited to the fields of resource economics and ecology. In the future, interdisciplinary integration and innovation need to be strengthened. On one hand, combine ecotoxicology to study the deep impact of water pollutants on ecosystems and refine the water quality correction module. On the other hand, introduce behavioral economics theory to analyze the decision-making mechanisms of water use behavior by the public and enterprises, enhancing the pertinence and effectiveness of policy intervention measures and enriching the research dimensions of the response mechanism of water resources carrying capacity.

Conclusion

By improving the water resources ecological footprint model, this paper effectively enhances the accuracy and practicality of assessments and reveals the dynamic changes and spatial difference characteristics of regional water resources carrying capacity. The research results indicate that the improved model can more scientifically reflect the interaction between human activities and the water resources system. In the future, it is necessary to continuously optimize model parameters and strengthen the application of multi-source data fusion and real-time monitoring technology to better guide the rational allocation of water resources and support the coordinated and sustainable development of regional social economics and the ecological environment.

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