

Research on the Water Ecological Carrying Capacity of the Harbin Section of the Songhua River Basin Based on Ecosystem Services

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Abstract:

Water ecological carrying capacity is a new concept that has emerged in recent years. Conducting water ecological carrying capacity assessments can help to control water pollution and restore water ecosystems. The Harbin section of the Songhua River Basin is a major source of living, industrial, and ecological water in Northeast China. The carrying capacity of the aquatic ecosystem is directly related to the ecological security of the basin and regional sustainable development. This article is based on the theory of ecosystem services and constructs a water ecological carrying capacity evaluation model based on driving force pressure state response (DPSR) and ecological service value. Starting from multiple aspects such as water quality, water quantity, social economy, and ecological engineering investment, the current situation, spatiotemporal variation characteristics, and main influencing factors of water ecological carrying capacity in Harbin section are analyzed, aiming to provide scientific basis for regional water resource management and ecological protection.

Keywords:

Songhua River Basin, Harbin Section, Water Ecological Carrying Capacity, Ecosystem Services

1. Introduction

In recent years, China has witnessed an accelerated population growth, an enhanced level of urbanization, and rapid socio-economic development. Consequently, the impacts of water resource scarcity and pollution on the ecological environment and socio-economic development within river basins have become increasingly significant, significantly weakening the carrying capacity of aquatic ecosystems for socio-economic development [1]. The concept of water ecological carrying capacity provides a theoretical foundation for quantifying the carrying limit of water ecosystems in the face of external pressures. From the perspective of ecosystem services, it not only focuses on water resource supply and water quality safety, but also comprehensively considers the regulating, cultural, supporting, and productive services provided by ecosystems to humans. This approach forms a multi-dimensional

and comprehensive evaluation system, providing scientific reference for watershed water environment management and ecological restoration.

2. Overview of the Study Area

2.1. Physical Geographical Features

The Songhua River basin is located in Northeast China, covering a total area of approximately 557,000 km² and serving as the main tributary of the Heilongjiang River. The Harbin section is situated in the middle and lower reaches, where the river channel gradually descends from north to south, passing through the city's core area and presenting a diverse riverbank landscape. The geomorphology within the basin is dominated by alternating alluvial plains and low hills. The riverbed and riparian zones are characterized by a rich mix of wetlands, farmland, and urban structures, with spatial heterogeneity playing a crucial role in regulating the functions of the aquatic ecosystem. Natural geographical conditions influence the flow path of water bodies and the transport of sediments, and also determine the habitat structure, species diversity, and the way ecosystem services are provided by the river channel. Therefore, understanding the impact of geographical fundamentals on water ecological carrying capacity is a prerequisite for formulating refined management strategies.

2.2. Hydrological and climatic characteristics

The hydrological characteristics of the Harbin section exhibit significant seasonal fluctuations, with runoff formation resulting from the combined effects of precipitation, snowmelt, and artificial water regulation. The annual average runoff is 2420m³/s, and the water volume can vary greatly between the wet and dry seasons, leading to notable spatial heterogeneity in flow rate and water quality carrying capacity. Water flow velocity, residence time, and hydrological connectivity of the river section all affect the dilution and sedimentation of pollutants as well as the assurance of ecological flow, thereby determining the buffering capacity of the ecosystem against external disturbances. Additionally, due to climatic factors, uneven precipitation distribution, extreme drought, and temperature changes can make the hydrological process more unstable, thereby exerting dynamic pressure on the structure and function of the ecosystem. The complexity of hydrological and climatic conditions has become an important environmental background for evaluating the water ecological carrying capacity of the Harbin section.

2.3. Socio-economic status

The Harbin section of the river basin serves as the economic, cultural, and densely populated hub of Northeast China, where socioeconomic activities are exerting increasing pressure on the aquatic ecosystem. The high urban population density, concentrated industrial layout, and escalating demand for energy and water have strained the relationship between water supply and demand. In recent years, industrial water consumption has been on the rise, accompanied by an increase in sewage discharge, creating a synergistic effect of driving force and pressure that impacts the functional stability of the aquatic ecosystem. Factors such as changes in land use patterns, urban expansion, and intensive agricultural cultivation further alter the ecological landscape of the basin, elevating the risk of water pollution load and habitat fragmentation.

2.4. Current status of aquatic ecological environment

The aquatic ecological environment in the Harbin section exhibits a complex spatiotemporal distribution, with water quality and ecological functions being comprehensively influenced by numerous factors. Monitoring results indicate that COD, TN, and NH₃-N are the primary pollutants, exerting a persistent impact on water quality. The water quality upstream is superior to that downstream, and it significantly improves during the wet season compared to the dry season, highlighting the important role of hydrological seasonality in the self-purification capacity of the ecosystem. Despite improvements in the coverage of wastewater treatment facilities and wetland restoration rates, the self-purification function of water bodies declines during low-flow periods, leading to delayed ecological responses and resulting in significant seasonal and spatial heterogeneity in the ecological carrying capacity. Furthermore, the degradation of ecological connectivity, cumulative effects of pollutants, and habitat fragmentation all hinder the full exertion of ecological service functions, posing potential threats to the long-term stability of the aquatic ecosystem.

3. Construction of An Evaluation Model for Water Ecological Carrying Capacity in the Harbin Section of the Songhua River Basin Based on Ecosystem Services

3.1. Evaluation Approach and Overall Framework

In the broader context of sustainable development, this paper constructs an evaluation system for the water ecological carrying capacity of the Harbin section of the Songhua River basin, grounded in the theory of ecosystem services. Based on the Driving Force-Pressure-State-Response-Restoration (DPRSR) model, it views socio-economic activities, environmental pressures, ecological states, and governance responses as a multi-layered system that interacts with each other. The evaluation framework aims to quantify the carrying capacity of the water ecosystem under different scenarios of human activity intensity and governance measures, while reflecting the multi-dimensional manifestations of ecosystem service functions, such as water supply, purification, regulation, and biological habitat services.

3.2. Construction of indicator system

The indicator system is designed based on the main characteristics of ecosystem service functions and aquatic ecological carrying capacity, and is divided into four subsystems.

Driving force indicators: total population, urbanization rate, industrial water consumption, agricultural irrigation water consumption, etc., reflecting the sources of pressure brought by socio-economic activities to the water ecosystem. Data from 2015 to 2022 shows that the industrial water consumption in Harbin increased from $1.62 \times 10^9 \text{ m}^3$ to $2.05 \times 10^9 \text{ m}^3$, and the urbanization rate rose from 62.5% to 68.9%.

Pressure indicators: Chemical Oxygen Demand (CODCr), Total Nitrogen (TN), Ammoniacal Nitrogen (NH₃-N), Total Phosphorus (TP), and pollutant emission intensity, which are used to measure the impact of environmental load on the water ecological status. During the dry season, COD is 28mg/L, and the average TN is 3.6mg/L, reflecting the seasonal fluctuation characteristics of pollution load.

Status indicators: Water Quality Index (WQI), ecological flow guarantee rate, wetland coverage rate, water body self-purification capacity, etc., are used to reflect the health status and service function level of the ecosystem. In 2021, the wetland coverage rate of the basin was about 12%, and the ecological flow guarantee rate was only 55% during the dry season, indicating that the ecological status is greatly affected by hydrological seasonal fluctuations.

Response indicators: sewage treatment rate, ecological restoration investment, construction area of ecological buffer zones, etc., reflecting the regulatory effect of management measures on carrying capacity mitigation and restoration. In recent years, the sewage treatment coverage rate has increased from 78% to 89%, and ecological restoration investment has been increasing by about 5% annually.

The indicator system encompasses four functional aspects of water ecosystem services: provisioning, regulating, supporting, and cultural. It takes into account the comprehensive evaluation needs of ecological status, social pressure, and management response, providing complete data support for carrying capacity quantification.

3.3. Determination of indicator weights

The weight of indicators is determined by combining “subjective expert judgment + objective data entropy method” to ensure the theoretical rationality and data objectivity[2]. Firstly, the Analytic Hierarchy Process (AHP) is employed to assign expert weights to four subsystems and their indicators, ensuring consistency between theoretical logic and ecological principles. Secondly, the entropy method is adopted to objectively calculate the variability of indicator data, quantify the contribution of information, and prevent biases caused by subjective weighting alone. Finally, the comprehensive weight is obtained through weighted fusion. Specifically, COD and TN account for 0.32 and 0.28 respectively in the weight of the pressure subsystem during the dry season, the ecological flow guarantee rate accounts for 0.25 in the state subsystem, and the sewage treatment rate accounts for 0.15 in the response subsystem, ensuring that the comprehensive carrying capacity index reflects both core pressures and governance effects as well as ecological status.

3.4. Construction of water ecological carrying capacity evaluation model

After integrating the indicator system and weights, this study constructs a weighted linear model to quantify the water ecological carrying capacity, as shown in formula

(1): $WEC = \sum_{i=1}^n w_i \cdot X_i$ In formula (1), WEC represents the comprehensive water ecological carrying capacity index, X_i denotes the standardized dimensionless index value, and w_i signifies the corresponding index weight.

The indicator standardization employs the range standardization method to convert data with different dimensions into a range of 0 to 1. The closer the carrying capacity index value is to 1, the stronger the carrying capacity of the aquatic ecosystem and the more perfect the ecological service function; when it approaches 0, it indicates that the system is under high pressure and at a critical state of carrying capacity. The model can be calculated based on year and season, reflecting the hydrological seasonality and the impact of management measures on carrying capacity. By inputting different socio-economic development and management scenario parameters (such as industrial water consumption growth rate, sewage reduction ratio, and

ecological water supplement amount) into the model, future population carrying capacity can be predicted, thus providing support for watershed management and policy formulation.

4. Evaluation and Regulation Countermeasures of Water Ecological Carrying Capacity in the Harbin Section of the Songhua River Basin

4.1. Assessment of ecosystem service functions

In the Harbin section of the Songhua River basin, the evaluation of aquatic ecosystem service functions should be comprehensively considered from four perspectives: provisioning, regulating, supporting, and cultural. The provisioning function primarily involves ensuring urban domestic and industrial water supply, with an average annual water supply of approximately $2.1 \times 10^9 \text{ m}^3$, including water for urban areas and irrigation of coastal farmland. The regulating function encompasses the abilities to dilute pollutants, self-purify, and regulate floods. The self-purification capacity during the dry season is only 65% of that during the wet season, with a strong seasonal carrying capacity. The supporting function is reflected in the provision of ecological habitats and the maintenance of biodiversity. The wetland coverage rate in the basin is approximately 12%, supporting the growth of fish and aquatic plants in the region. The cultural function involves riverbank landscapes, ecological education, and recreational value. Through quantitative assessment of ecosystem services, it can be found that due to reduced flow and pollutant accumulation during the dry season, service functions significantly decline. The service function carrying capacity in the urban core area and downstream tributary confluence areas is relatively low, indicating spatial heterogeneity in the provision of various services by the aquatic ecosystem. This provides a quantitative basis for subsequent carrying capacity evaluation and management strategies.

4.2. Comprehensive evaluation of water ecological carrying capacity

Based on the DPRSR model and the ecosystem service-oriented indicator system, the comprehensive water ecological carrying capacity index of the Harbin section of the Songhua River is obtained through weighted calculation of multi-dimensional indicators. The driving force subsystem indicators show that industrial water consumption has increased by 3% annually, and the urbanization rate has risen from 62.5% to 68.9%, increasing the pressure on the system. The contribution rate of COD, TN, and $\text{NH}_3\text{-N}$ in the pressure subsystem during the dry season is greater than 83%, reflecting the accumulation of pollution load during low flow periods. The evaluation of the state subsystem indicates that water quality upstream is better than downstream, and water quality during the wet season is better than during the dry season, with the self-purification capacity of the water body being greatly affected by seasonal flow fluctuations. The response subsystem is reflected in the improvement of sewage treatment rate and ecological water replenishment mechanism, but the effect on pressure mitigation is still limited. The comprehensive index calculation results show that the carrying capacity index can drop to 0.48 during the dry season and rise to 0.67 during the wet season, indicating that the system has significant seasonality and spatial heterogeneity. The comprehensive evaluation results show that the water ecological carrying capacity is in a moderately low state under the current socio-

economic development and governance level, with critical carrying risks, especially in areas with concentrated industrial emissions and during low flow periods.

4.3. Analysis of the driving mechanism of water ecological carrying capacity

The driving mechanism of water ecological carrying capacity in the Harbin section is the coupling effect of multi-scale and multi-variable factors. Socio-economic activities, due to the increase in industrial water use and the advancement of urbanization, have increased the load on the ecosystem, which is the main driving factor [3]; water pollutant load, spatial distribution of pollution sources, and decreased flow during the dry season constitute the main pressures, significantly inhibiting water quality status and self-purification capacity; ecological flow assurance rate, wetland restoration, and sewage treatment rate belong to the response adjustment mechanism, but they exhibit lagging and localized characteristics, making it difficult for them to play a buffering role. From the results of principal component analysis, it can be seen that in the pressure subsystem, the contribution rates of COD, TN, and NH₃-N are all greater than 80%, which are the main limiting factors for carrying capacity recovery; the ecological flow assurance rate has the best control effect on seasonal carrying fluctuations. There is a complex nonlinear feedback loop among the four elements of driving force, pressure, state, and response, leading to spatiotemporal heterogeneity in water ecological carrying capacity, and it is particularly sensitive to system stability in low flow years and high pollution input years [3]. The main pressures are constituted by water pollutant load, spatial distribution of pollution sources, and decreased flow during the dry season, which significantly inhibit water quality status and self-purification capacity. The ecological flow assurance rate, wetland restoration, and sewage treatment rate belong to the response adjustment mechanism, but they have characteristics of lag and partiality, making it difficult for them to play a buffering role. According to the results of principal component analysis, the contribution rates of COD, TN, and NH₃-N in the pressure subsystem are all greater than 80%, which are the main limiting factors for the restoration of carrying capacity; the ecological flow assurance rate has the best control effect on seasonal carrying fluctuations. There is a complex nonlinear feedback loop among the four elements of driving force, pressure, state, and response, which leads to spatiotemporal heterogeneity in water ecological carrying capacity, and is particularly sensitive to system stability in low-flow years and high-pollution input years.

4.4. Countermeasures to enhance the carrying capacity of water ecology

To enhance the water ecological carrying capacity of the Harbin section of the Songhua River, concerted efforts should be made from three levels: institutional, engineering, and ecological management. From an institutional perspective, it is necessary to raise the water pollution emission standards for the basin, especially the annual reduction targets for COD, TN, and NH₃-N, to ensure that driving forces and pressures are controllable [4]. From an engineering perspective, it is necessary to accelerate the upgrading and renovation of wastewater treatment plants, the restoration and expansion of wetlands, and ecological water replenishment projects, in order to enhance the self-purification capacity of water bodies and the guarantee rate of ecological flow, thereby alleviating the carrying pressure during the dry season. From an ecological management perspective, measures such as constructing riparian buffer zones, controlling pollution at the source, and regulating water quality in tributaries can be implemented to improve habitat connectivity and biodiversity

support functions. Additionally, it is necessary to establish a monitoring and early warning system for water ecological carrying capacity, and incorporate the carrying capacity index into watershed planning and urban development decisions, in order to achieve multi-objective management and dynamic adjustment. In the long run, relying on the mutual promotion of governance and ecological restoration, it is possible to achieve the goal of enhancing the service functions of the water ecosystem and coordinating with socio-economic development, ensuring the long-term stable carrying capacity of the water ecosystem in the Harbin section under the background of sustainable development.

5. Conclusions

Ecological footprint is an important indicator for measuring the sustainable development of water and soil resources, and it is also a theoretical model quantified based on land area. The water ecosystem is a nonlinear and complex system with feedback [5]. Research on the water ecological carrying capacity based on ecosystem services helps to understand the ecological security issues in river basins and provides a theoretical basis for scientific management of water resources and ecological restoration. To enhance the water ecological carrying capacity of the Harbin section of the Songhua River basin, comprehensive management and multi-party collaboration are required to achieve the goal of coordinating ecosystem health with socio-economic development. As an important indicator for measuring the sustainable development of water and soil resources, ecological footprint can provide a quantitative tool for sustainable management of river basins.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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