

Study on Water Ecological Carrying Capacity in the Harbin Section of the Songhua River Basin under the Context of Sustainable Development

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Abstract:

In recent years, China's socio-economic development has accelerated, and the demand for industrial water has significantly increased, resulting in a shortage of water resources and pollution of the water environment, posing a threat to the health of the aquatic ecosystem. In this context, the Harbin section of the Songhua River basin is an important source of living, industrial, and ecological water in Northeast China, facing multiple pressures in carrying human activities and ecological service functions. This article is based on the concept of sustainable development and establishes a water ecological carrying capacity evaluation system using the Driver Pressure State Response (DPRS) model. Quantitative analysis and model prediction are conducted to reveal the current status, spatiotemporal changes, and influencing factors of the water ecological system carrying capacity in the Harbin section, providing decision-making references for regional water resource management and watershed ecological protection.

Keywords:

Songhua River Basin, Harbin Section, Water Ecological Carrying Capacity, Sustainable Development

1. Introduction

Water and soil resources are the most important natural resource elements on Earth, and their relationship is crucial for the stability of ecosystems and regional development [1]. Land resources are the carrier of water resources, carrying the development, utilization, and protection of water resources. In the context of rapid urbanization and industrialization, water ecological carrying capacity has become an important indicator for evaluating regional water environmental carrying capacity and sustainable development potential, and is increasingly receiving attention from academia and policy makers. Water ecological carrying capacity refers to the maximum load capacity that a water ecosystem can withstand the impact of human activities within a certain time and space range, in order to maintain ecological balance and functional integrity. It involves many aspects such as water resource

supply, water environment quality, ecosystem health, and water resource utilization efficiency.

2. Overview of the Research Area

The Songhua River Basin is one of the most important water systems in Northeast China, with a basin area of 557000 square kilometers. It is a tributary of Heilongjiang Province, and the hydrological conditions in the basin are jointly controlled by seasonal precipitation and snowmelt. The average runoff is about 2420m³/s, and the spatiotemporal variation of runoff is relatively complex. The Harbin section belongs to the control unit from the middle to the lower reaches of the Songhua River. It shoulders the tasks of regional urban living, industrial production, and agricultural irrigation water, and is an important system for urban water supply, ecological restoration, and landscape services. This section of the river is located in the central urban area of Harbin, and the hydrological process has obvious seasonal changes. There is a significant difference in water volume between the dry and wet seasons, which has a certain impact on the structure and function of the aquatic ecosystem. In addition, according to principal component analysis based on monitoring data in 2015, chemical oxygen demand (CODCr), total nitrogen (TN), and ammonia nitrogen (NH₃-N) are the main pollution indicators of water quality in the Harbin section.

3. Evaluation Method for Water Ecological Carrying Capacity

This article is based on the theories of sustainable development and system ecological engineering, and adopts the Driver Pressure State Response Restoration (DPRSR) framework as the main logical framework for water ecological carrying capacity. This framework is based on the extension and deepening of classic evaluation systems such as PSR/DPSIR, while considering the causal feedback relationship between human activity driving factors, negative pressure variables, ecological state representation, and governance response mechanisms. When evaluating, the original data of water quality, water quantity, economic and social, and ecological engineering investment in the Harbin section over multiple years are first screened for indicators, and a four subsystem indicator system is established for driving force, pressure, status, and response. This system not only includes common socio-economic indicators and environmental quality status indicators, but also takes into account ecological response indicators such as regional ecological flow guarantee rate and sewage treatment rate to ensure multidimensional characterization of water ecological carrying capacity.

In order to eliminate the comprehensive evaluation impact caused by different dimensional indicators, this article standardized all original indicators, converting data of different physical dimensions into a unified dimensionless indicator, which facilitates weight calculation and comprehensive comparison in the future. The weight of indicators is determined by a combination of subjective expert judgment and objective statistics, namely the integration of Analytic Hierarchy Process (AHP) and Entropy Method, in order to balance theoretical logical judgment with the inherent information of data, and improve the objectivity and robustness of weight assignment [2].

4. Evaluation Results and Analysis of Water Ecological Carrying Capacity of Harbin Section in Songhua River Basin

4.1. Analysis of evaluation results for each subsystem (driving force pressure state response)

When using the DPRSR framework to quantitatively evaluate the water ecological carrying capacity of the Harbin section of the Songhua River Basin, there are significant structural differences and spatiotemporal variations in each subsystem. In the driving force subsystem, as the urbanization rate and industrial water demand in Harbin continue to increase (with the number of industrial water outlets in the urban area remaining in the 9-12 range), the driving force of socio-economic activities on the ecosystem is strengthened, but at the same time, it also exacerbates the system's pressure state; In the pressure subsystem, the water pollutant load is mainly composed of chemical oxygen demand (COD (Cr)), total nitrogen (TN), and ammonia nitrogen (NH₃-N). The main components are 69.97%, 69.18%, and 74.23% during the wet season, and 83.77%, 83.60%, and 83.09% during the dry season. This indicates that the pollution load increases significantly with changes in flow rate, and the inhibitory effect on ecological status is most severe during low flow periods. The evaluation results of the state subsystem indicate that on typical water quality sections, the upstream water quality is significantly better than the downstream zone, and the overall water quality during the wet season is better than that during the dry season, which is consistent with long-term monitoring results. The response subsystem refers to the effectiveness of governance measures and ecological engineering. Although the coverage of sewage treatment facilities and ecological water replenishment mechanisms have been improved, the self purification capacity of water bodies is still in a weakened stage. From the system evaluation results, it can be seen that the combined effect of driving force and pressure poses a serious threat to the aquatic ecological status, and responsive measures cannot effectively compensate for the ecological losses caused by the pressure amplification effect. Therefore, there are significant non-linear differences in the comprehensive carrying capacity among various subsystems.

4.2. The spatiotemporal variation characteristics of comprehensive water ecological carrying capacity

The comprehensive carrying capacity index, measured by a multi index fusion model, can reflect the dynamic changes of the aquatic ecosystem in the Harbin section of the Songhua River. According to years of monitoring and model results, the overall carrying capacity index has obvious seasonal and annual trends. During the wet season, due to the increase in water flow and the significant dilution of pollutants, the comprehensive carrying capacity index is in a relatively high range; During the dry season, due to the decrease in flow, the self purification capacity weakens, pollutant concentration accumulates, and the carrying capacity index significantly decreases or even approaches the critical threshold. Research has shown that the contribution thresholds of COD, TN, and other factors to the overall carrying capacity have significant critical characteristics. In high flow years, the COD environmental capacity can reach 219723.26t and the TN environmental capacity can reach 8040.78t, indicating that there is still some buffer space left in the system under certain hydrological conditions. However, in low flow years or dry seasons, the buffer space is significantly reduced, and the carrying capacity can easily reach a critical or

overloaded state. Comprehensive spatiotemporal analysis also shows that there is significant spatial heterogeneity in the carrying capacity levels between different sections. Hot spots with low carrying capacity often appear in the urban core section and downstream tributary confluence section, due to the input of pollutants from tributaries, uneven distribution of flow velocity, and decreased habitat connectivity [3]. Therefore, the comprehensive carrying capacity of the Harbin section of the Songhua River is greatly affected by long-term human activities, and is also sensitive to seasonal hydrological fluctuations, with complex and variable spatiotemporal dynamic changes.

4.3. Analysis of influencing factors

The influencing factors of water ecological carrying capacity in Harbin section are the result of the combined effects of individual factors, community factors, environmental factors, and systemic factors. The mismatch between pollutant input intensity and treatment response capability is the main limiting factor. The contribution rates of COD, TN, and NH₃-N are dominant during both wet and dry seasons, with COD, TN, and NH₃-N contributing more than 80% during the dry season. The nitrogen and oxygen demand indices are the main factors limiting the recovery of carrying capacity. Flow regulation and ecological flow guarantee are hydrodynamic factors that affect the spatiotemporal heterogeneity of carrying capacity. Due to the significant differences between dry and wet seasons, the self purification capacity and diffusion capacity of water bodies differ fundamentally between wet and dry periods. Therefore, the ecological flow guarantee rate directly affects the seasonal fluctuation amplitude of carrying indicators [4]. In addition, source control and system response strategies have a significant regulatory effect on carrying capacity, but there is still a lag in current response measures. For example, although there is an increasing trend in the coverage of sewage treatment and the restoration rate of ecological wetlands, the release of their buffering functions requires a longer time scale. At the same time, socio-economic factors such as the increasing demand for urban drinking water, adjustments in industrial layout, and changes in land use are constantly changing the driving force background of water ecosystems from a macro perspective. The results of quantitative coupling analysis indicate that fluctuations in carrying capacity are not only directly caused by external pressures, but also by internal feedback mechanisms (ecological response lag, material accumulation effects) and long-term accumulation of external driving forces, revealing the internal generation mechanism of changes in the spatiotemporal structure of carrying capacity.

5. Prediction and Development Model Analysis of Water Ecological Carrying Capacity in Harbin Section of Songhua River Basin

5.1. Model parameter setting and scenario construction

In order to quantitatively predict the water ecological carrying capacity of the Harbin section of the Songhua River Basin, this paper establishes a scenario simulation model based on historical monitoring data and a driving force, pressure, state, and response indicator system. The model parameters include the socio-economic development rate (population growth rate, industrial water consumption growth rate), ecological governance investment intensity, total pollutant emissions, and hydrological variables (flow rate, precipitation, etc.). Time series prediction methods such as BP neural network and Markov chain are used to fit the future trends

of the indicator data, which are used as input variables for carrying capacity simulation prediction. On this basis, in order to explore the changes in carrying capacity under different governance paths, this article proposes three typical model scenarios. The conventional development model assumes that the existing level of governance and economic drivers will not undergo significant changes due to major policy changes. In this case, the growth rates of industrial water consumption and sewage discharge are 3% and 2.5% per year, respectively; The comprehensive development model has added moderate measures such as sewage reduction and wetland ecological restoration on the basis of conventional practices; The ecological priority development model requires stricter control of pollutant emissions, ecological flow guarantee mechanisms, and large-scale ecological restoration projects to control the annual growth of pollutants below 1% and increase the weight of ecological response indicators. Scenario constraints endow the model with different combinations of driving forces and response characteristics, providing richer policy reference significance for predicting possible paths of future carrying capacity.

5.2. Analysis of changes in carrying capacity under different development models

5.2.1. Analysis of Conventional Development Models

Under the conventional development model, due to the continuous strengthening of economic and industrial drivers and insufficient pollution control measures, the predicted system carrying capacity shows a slow decline trend. Taking the predicted value of the comprehensive carrying capacity index as an example, during the 2021-2030 prediction period, the index can drop to 0.48 by 2025, approaching the critical carrying threshold. This trend reflects the negative feedback effect brought by the growth of driving forces and pressures on the status and response of the Harbin section of the Songhua River without strengthening governance measures, resulting in a decrease in carrying capacity. In this mode, the carrying capacity index decreases significantly during the dry season, and there is a risk of critical or mild overload when traditional water self purification mechanisms are unable to digest the increasing pollutant load.

5.2.2. Analysis of Comprehensive Development Model

The comprehensive development model relies on moderate intensity sewage treatment, mesoscale ecological restoration projects, and ecological water replenishment measures, which can partially regulate the imbalance between driving forces and pressures. The simulation results show that the comprehensive carrying capacity index will remain between 0.53 and 0.61 from 2025 to 2030, which is about 0.05 to 0.08 higher than the conventional model. From this, it can be seen that adopting comprehensive governance measures can to some extent slow down the trend of declining carrying capacity and improve the buffering capacity of ecosystems against external disturbances. The improvement of sewage treatment capacity and moderate increase in wetland area have increased the removal rate of major pollutants such as COD and TN, improved water quality indicators, and made the comprehensive carrying capacity more stable. In addition, ecological water replenishment measures have improved the ecological flow guarantee rate and effectively solved the seasonal differences in the decline of carrying capacity during the dry season.

5.2.3. Prediction Results Comparison and Optimization Recommendations

A horizontal comparison of the carrying capacity prediction results under three development models reveals that the conventional model exhibits a significant decline trend, while the comprehensive and ecological priority models can enhance carrying capacity and curb the spread of negative trends. Based on the model predictions, the following optimization recommendations are proposed: First, strengthen the regulatory standards for water pollution discharge in the basin, particularly by implementing stricter regulations on key pollutant indicators such as COD and TN, and formulate annual reduction plans to alleviate the pressure on the system. Second, improve water resource allocation and ecological replenishment measures to mitigate carrying capacity stress during dry periods. Finally, establish a multi-objective management mechanism that integrates carrying capacity monitoring and prediction outcomes into regional development plans, thereby enhancing policy consistency and system adaptability.

6. Conclusions

The aquatic ecosystem is a complex, nonlinear, multi-loop dynamic feedback system where the elements within exhibit nonlinear relationships and intricate causal connections [5]. The study of water ecological carrying capacity can provide a systematic understanding of regional water ecological security issues, and provide a theoretical basis for establishing scientific and reasonable water resource management and ecological protection policies. In the context of sustainable development, improving the water ecological carrying capacity of the Harbin section of the Songhua River Basin requires comprehensive management and multi-faceted cooperation to achieve the coordinated unity of ecosystem health and socio-economic development.

Conflicts of Interest

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

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