Water Environment Carrying Capacity Assessment in Kyrgyzstan Based on Sustainable Development Goals (Postprint)

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Abstract

This study references the evaluation indicators of the 2030 Sustainable Development Goals (SDGs), employs the entropy method and Analytic Hierarchy Process to determine indicator weights, utilizes Principal Component Analysis to examine the temporal trends of water environment carrying capacity in Kyrgyzstan from 2006 to 2020, and identifies the key influencing factors affecting water environment carrying capacity in Kyrgyzstan through the vector modulus method. The results show that the water environment carrying capacity in Kyrgyzstan exhibited an overall increasing trend from 2006 to 2020. The water environment and socioeconomic subsystems facilitated the continuous increase of water environment carrying capacity, while the water ecology and water resources subsystems constrained it. Population density, water stress level, water body area, and per capita renewable water resources constitute the key influencing factors limiting water environment carrying capacity. Increasing urbanization rate, improving water use efficiency, reducing wastewater discharge volume, and enhancing wastewater treatment rate are effective measures for improving water environment carrying capacity in Kyrgyzstan.

Full Text

Abstract

Drawing on evaluation indicators from the Sustainable Development Goals (SDGs), this study employs the entropy method and analytic hierarchy process to determine indicator weights, utilizes principal component analysis to examine trends in Kyrgyzstan' s water environmental carrying capacity from 2006 to 2020, and identifies the primary influencing factors through the vector modulus method. The results demonstrate that Kyrgyzstan' s water environmental carrying capacity exhibited an overall strengthening trend during 2006–2020.

The water environment and socioeconomic subsystems promoted continuous enhancement of carrying capacity, while water ecology and water resource subsystems constrained it. Population density, water scarcity intensity, water body area, and per capita renewable water resources represent the main limiting factors. Increasing urbanization rates, improving water use efficiency, reducing wastewater discharge, and enhancing wastewater treatment rates constitute effective pathways for improving Kyrgyzstan' s water environmental carrying capacity.

Keywords: water environmental carrying capacity; Sustainable Development Goals (SDGs); principal component analysis; vector modulus method; Kyrgyzstan

Introduction

Population surges driven by social development have intensified environmental pressures and resource consumption, with water environmental degradation emerging as both a global environmental challenge and a constraint on regional sustainable development. The concept of sustainable development has gained increasing attention, leading to the integration of water-related concepts and the formation of numerous water environmental carrying capacity studies that reflect the maximum capacity of water environments to support sustainable population, economic, and social development under specific conditions. In September 2015, the UN General Assembly adopted "Transforming Our World: The 2030 Agenda for Sustainable Development," wherein the 17 Sustainable Development Goals (SDGs) guide global sustainability across economic, social, and environmental dimensions, emphasizing harmonious coexistence between humans and nature. This framework provides new perspectives and methods for integrating specific SDG strategies with water environmental carrying capacity analysis.

Many scholars have referenced SDG indicators when evaluating regional development status, constructing indicator systems from various perspectives, with water-related metrics serving as crucial tools for assessing water environmental sustainability. Extensive research has employed diverse methods for water environmental carrying capacity evaluation, including fuzzy mathematics, system dynamics, artificial neural networks, vector modulus method, principal component analysis, comprehensive evaluation indicators, and matter-element extension models. These approaches typically involve constructing water environmental indicator systems and establishing models to calculate evaluation values, thereby revealing trends across different watersheds or regions.

Kyrgyzstan, a major agricultural and pastoral nation, faces significant water quality degradation from pesticide and fertilizer residues in irrigation districts, with agricultural pollution representing a primary cause of soil and water salinization. Population growth, inadequate wastewater management systems, and insufficient infrastructure have led to increasing contamination of rivers and groundwater by organic matter, nutrients, and pathogens. Extensive mineral resource extraction has further left heavy metals and mining pollutants in water bodies and soil. While water environmental issues have become increasingly prominent, existing research has primarily focused on water resources and pollution, such as water chemistry and heavy metal assessments in the Issyk-Kul Basin, and the development of water use efficiency datasets using MODIS data to address evaluation challenges. Water environmental carrying capacity assessment constitutes an essential component of the Belt and Road Initiative, providing references for SDG-based evaluation and indicator system construction.

This study examines Kyrgyzstan as the research area, selecting specific indicators from SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 8 (Sustainable Economic Growth), and SDG 11 (Sustainable Cities) based on regional conditions. It establishes a comprehensive evaluation index system for Kyrgyzstan' s water environmental carrying capacity, employs principal component analysis to evaluate temporal trends from 2006 to 2020, and uses vector modulus method to analyze primary influencing factors, providing scientific foundations for future water environmental protection and socioeconomic sustainable development.

1.1 Study Area Overview

The Kyrgyz Republic (Kyrgyzstan) is located in northeastern Central Asia, covering approximately 198.50$×10^{3}$ km^{2} as a typical landlocked country. It borders China to the southeast and east, Uzbekistan to the southwest, Tajikistan to the south, and Kazakhstan to the north and northeast. With multi-year average precipitation of 7.7$×10^{9}$ m^{3}, Kyrgyzstan possesses abundant rivers and lakes with substantial total water resources, yet uneven distribution creates water scarcity in some regions. As an agriculture-dominated nation, irrigation accounts for 90% of total water withdrawal, with severe pollution from pesticides, fertilizers, and livestock waste causing significant water quality fluctuations. Incomplete urban water supply and drainage infrastructure, coupled with low irrigation efficiency, contribute to water resource depletion and environmental degradation. Current water resource management and environmental protection efforts remain inadequate.

1.2 Data Sources

Data for 15 indicators from 2006–2020 were collected. GDP, population density, urbanization rate, wastewater discharge, ammonia nitrogen emissions, and national environmental protection budget expenditure data were obtained from the National Statistical Committee of the Kyrgyz Republic and "Environmental Protection" reports (including ecological status of the Issyk-Kul region) via http://www.stat.kg. Wastewater discharge and ammonia nitrogen emission data originated from hydrometeorological station statistics of Kyrgyzstan' s

Hydrometeorological Service. Water use efficiency, water scarcity intensity, forest cover proportion, and water body extent data were sourced from the UN Sustainable Development Goals database (https://www.sdg6data.org) and Index Mundi (https://www.indexmundi.com). Per capita renewable water resources and fertilizer consumption data were derived from Knoema (https://cn.knoema.com).

1.3 Construction of Water Environmental Carrying Capacity Index System

The index system was constructed by comprehensively considering Kyrgyzstan's natural geography, economic development status, and selecting SDG indicators closely related to water environmental carrying capacity. While SDG 6 (Clean Water and Sanitation) provides specific reference indicators, direct assessment requires additional metrics from SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) for water environment sustainability, plus socioeconomic indicators from SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health), SDG 8 (Sustainable Economic Growth), and SDG 11 (Sustainable Cities). Consequently, a four-dimensional evaluation system integrating socioeconomic, water resources, water environment, and water ecology dimensions was established (Table 1).

To comprehensively account for both subjective judgment and objective indicator dispersion, this study combines subjective and objective weighting methods—entropy method and analytic hierarchy process—calculating comprehensive weights (w) for each indicator through multiplicative integration:

$$w_i = \theta_i \times \gamma_i$$

where represents the weight calculated by the entropy method and γ represents the weight calculated by the analytic hierarchy process for the i-th indicator.

1.4 Water Environmental Carrying Capacity Evaluation Methods

Principal component analysis and vector modulus method were employed to evaluate Kyrgyzstan' s water environmental carrying capacity trends from 2006-2020 and identify primary influencing factors.

1.4.1 Principal Component Analysis

Principal component analysis is a widely used dimensionality reduction algorithm that reflects all influencing factors through a limited number of key factors, eliminating multicollinearity and improving analytical efficiency. The procedure involves: (1) 极差标准化方法 for data normalization; (2) correlation coefficient matrix assessment; (3) determination of principal component numbers based on eigenvalues and cumulative contribution rates; (4) principal component score calculation; and (5) comprehensive score computation using contribution rates as weights to establish evaluation standards.

1.4.2 Vector Modulus Method

The vector modulus method quantifies evaluation results by representing normalized indicator values multiplied by their weights as vectors. For analyzing the m-th evaluation year’ s n-th component, a vector model is established. In comparative evaluation across years, E (j = 1,···,m) represents evaluation values, m denotes evaluation years, n indicates component numbers, and w (i = 1,···,n) represents weights for each evaluation component. The evaluation value E is expressed as:

$$E_j = \sum_{i=1}^{n} w_i \bar{E}_{ij}$$

where w is the weight of the i-th water environmental carrying capacity indicator and $\bar{E}_{ij}$ represents dimensionless normalized values of each indicator.

2.1 Principal Component Analysis-Based Evaluation

Following 极差标准化法 for dimensionless standardization, principal component analysis revealed that the first four principal components achieved a cumulative contribution rate of 91.555% with eigenvalues exceeding 1, essentially encompassing most original information and enabling water environmental carrying capacity description. The first principal component showed significant positive correlation with water use efficiency, per capita water withdrawal, and forest cover proportion, and significant negative correlation with population density, reflecting influences from socioeconomic, water resource, and water ecological aspects. The second principal component exhibited significant positive correlation with wastewater treatment rate and discharge, and negative correlation with ammonia nitrogen emissions and urbanization rate, covering primary water environment and socioeconomic factors. The third principal component demonstrated significant positive correlation with ammonia nitrogen emissions and water scarcity intensity, and negative correlation with fertilizer consumption, encompassing key water resource and water environment factors. These four components collectively cover socioeconomic, water environment, water ecology, and water resource dimensions, demonstrating significant correlations and validating the index system’ s suitability.

Comprehensive scores calculated using principal component contribution rates as weights (Table 4) indicate that Kyrgyzstan’ s water environmental carrying capacity generally increased from 2006–2020, with rapid improvement during

2015-2018 and slower but consistent growth in other years. The 2020 score of 1.157 significantly exceeded the 2006 value of -1.547, confirming overall enhancement despite slow progression.

2.2 Factor Analysis

To further analyze primary change factors, vector modulus method evaluated subsystem and individual indicator impacts. Weight analysis using analytic hierarchy and entropy methods yielded combined weights (Table 5), with higher weights assigned to population density, urbanization rate, water scarcity intensity, wastewater discharge, and water body extent.

Subsystem evaluation results (Figure 1) reveal that water environment and socioeconomic subsystems significantly influence overall carrying capacity. The water environment subsystem showed high overall levels, rising during 2006-2018 with a slight decline after 2018 peak values, primarily due to reduced wastewater discharge and improved treatment rates. The socioeconomic subsystem demonstrated steady upward trends in urbanization rate and per capita GDP, though population density declines constrained carrying capacity. The water resource subsystem fluctuated, decreasing in 2010 due to reduced total water resources, then rising steadily until 2018 before slowly increasing again, reflecting persistent pressure from population growth and social development requiring improved water use efficiency. The water ecology subsystem exhibited overall decline, with forest cover and water body extent reductions becoming major limiting factors despite slight 2018 improvements.

Indicator-level analysis (Figure 2) shows urbanization rate, water use efficiency, per capita water withdrawal, wastewater discharge, and treatment rate as favorable factors, while population density, water scarcity intensity, water body extent, and per capita renewable water resources act as constraints. Ammonia nitrogen and fertilizer consumption showed minor upward trends but limited impact.

3 Conclusions

This study evaluated Kyrgyzstan’ s water environmental carrying capacity using SDG-relevant indicators, establishing a “socioeconomic-water resources-water environment-water ecology”index system. Principal component analysis of 2006-2020 data revealed overall upward trends (except 2010), with rapid improvement during 2015-2018 and slower progression in other years, primarily due to constrained water ecology and water resource subsystems. Vector modulus analysis identified water environment and socioeconomic subsystems as primary drivers, while water ecology declines and water resource fluctuations served as limiting factors. Key limiting indicators included population density, water scarcity intensity, water body extent, and per capita renewable water resources, whereas urbanization rate, water use efficiency, wastewater discharge reduction, and treatment rate improvements offered effective enhancement pathways. Policy measures including the Water Law implementation and water resource rational utilization policies significantly improved wastewater management, though strengthened environmental monitoring and treatment facility upgrades remain essential.

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Note: Figure translations are in progress. See original paper for figures.