Spatiotemporal Patterns of Water Resources Carrying Capacity and Subsystem Coupling Coordination in Southern Xinjiang (Postprint)

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Date: 2023-03-13T00:00:00+00:00

Abstract

The supply-demand contradiction between inherent water scarcity and anthropogenic water consumption in Southern Xinjiang originates from long-standing natural factors and the impact and destruction of production activities on the ecological environment. Addressing this contradiction requires the formulation of scientifically sound water use plans. In view of the current situation of water resources supply and demand in Southern Xinjiang, this study constructs an evaluation index system for regional water resources carrying capacity comprising 24 indicators based on three dimensions: water resources, socio-economic development, and ecological environment. Employing the entropy weight-TOPSIS method and coupling coordination degree model, the spatio-temporal evolution of water resources carrying capacity and the coupling coordination degree among subsystems in Southern Xinjiang from 2005 to 2020 is quantitatively evaluated. The results indicate: (1) The overall level of water resources carrying capacity in Southern Xinjiang is relatively low. The water resources carrying capacity in the Bayingolin Mongol Autonomous Prefecture is comparatively better, while Aksu and Kashgar regions exhibit a fluctuating upward trend. The Kizilsu Kirghiz Autonomous Prefecture and Hotan region show an overall trend of initial decline followed by gradual increase. (2) The coupling coordination degree in Southern Xinjiang demonstrates an upward trend, but remains at a low-level coupling stage (0.2

Full Text

Spatio-temporal Pattern of Water Resource Carrying Capacity, Coupling and Coordination of Subsystems in Southern Xinjiang

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Abstract

The contradiction between water supply and demand in southern Xinjiang, arising from both natural water scarcity and anthropogenic impacts, stems from long-term natural accumulation and the effects of production activities on the ecological environment, including its destruction. Addressing this supply-demand conflict requires the formulation of scientifically sound and comprehensive water management plans. Focusing on the current state of water resources supply and demand in southern Xinjiang, this study constructs a water resource carrying capacity evaluation index system comprising 24 indicators based on three dimensions: water resources, socioeconomic development, and ecological environment. Using the entropy weight-TOPSIS method and coupling coordination model, we quantitatively evaluate the spatio-temporal evolution of water resource carrying capacity and inter-subsystem coupling coordination in southern Xinjiang from 2005 to 2020. The results demonstrate that: (1) The overall water resource carrying capacity in southern Xinjiang remains low. Bayingol Mongolian Autonomous Prefecture exhibits relatively favorable carrying capacity, though with substantial fluctuations and unstable trends. Aksu and Kashgar regions show overall fluctuating upward trends with similar growth rates, achieving over 40% increase in comprehensive evaluation values by 2020 compared to 2005. Kizilsu Kirghiz Autonomous Prefecture and Hotan region demonstrate initial fluctuating declines followed by gradual recovery, with Hotan showing particularly large fluctuations. (2) From 2005 to 2020, the water resources-socioeconomic-ecological environment system in southern Xinjiang remained in a low-level coupling stage, indicating poor inter-subsystem correlation. By 2020, the coupling coordination degree transitioned from serious 不协调 to basic 不协调, showing an overall upward trend with considerable room for improvement. Bayingol Mongolian Autonomous Prefecture achieved the highest coupling coordination level, progressing from mild 失调衰退型 to 濒临失调衰退型. The other four prefectures advanced from moderate 失调衰退型 to mild 失调衰退型. Based on comprehensive evaluation values, Bayingol, Aksu, and Kashgar belong to the water resources lagging type; Kizilsu represents the socioeconomic-ecological environment interaction lagging type; and Hotan falls under the socioeconomic lagging type. (3) Spatially, coupling coordination degree shows strong correspondence with geographical location, manifesting as eastern superiority over central and western regions. Bayingol exhibits the best coordination level, while Kizilsu' s

western border location and complex geography result in slower improvement. Aksu, Kashgar, and Hotan display similar change rates and stable growth trends.

Keywords: water resources carrying capacity; coupling coordination; water resources-socioeconomic-ecological environment; southern Xinjiang

1. Introduction

Water resources constitute the root of all issues in the socio-economic and ecological development of arid northwest China. Current research on water resources in this region primarily focuses on vulnerability, optimal allocation, and predictive simulation, with relatively few studies examining coordinated development among water resources, socio-economics, and ecological environment. Balancing the relationship between socio-economic development and water resources/ecological environment represents one of the most urgent challenges facing northwestern arid regions. Water resources, socio-economics, and ecological environment form a composite system characterized by mutual constraints and promotion. Water resources serve as the foundation for socio-economic development and ecological construction, while socio-economic development consumes and degrades water resources and ecological environment, which in turn affects water quality and constrains socio-economic progress.

Water resource carrying capacity is a critical indicator describing the capacity of regional water resources to support socio-economic development and ecological construction. While international scholars focus primarily on water resource planning, sustainable utilization, and security, Chinese research has concentrated on basins, regions, and cities. Studies on Xinjiang' s water resources have examined areas such as Kashgar, the entire Xinjiang region, and the Tarim River Basin, but comprehensive research on southern Xinjiang as a whole remains scarce. Southern Xinjiang, a typical arid and semi-arid region, possesses abundant total water resources but limited per capita availability and uneven spatio-temporal distribution. Coupled with poor natural conditions, these factors have constrained socio-economic development. Understanding the current water resource status and the coupling coordination development law among water resources, socio-economics, and ecological environment is crucial for scientific water resource planning and promoting sustainable development and ecological civilization construction in southern Xinjiang.

2. Research Methods

2.1 Study Area Overview Southern Xinjiang comprises five prefectures: Bayingol Mongolian Autonomous Prefecture (Bayingol), Aksu Region, Kizilsu Kirghiz Autonomous Prefecture (Kizilsu), Kashgar Region, and Hotan Region, covering 1.0863×10^{6} km^2 (approximately 3.76% of Xinjiang' s total area). The region is dominated by mountains and basins, with oasis areas accounting for only 4.23%. The ecological environment is fragile, characterized by scarce rainfall, extensive desert areas, limited usable land resources, and sparse vegetation. In 2020, the permanent population reached 11.9517 million (28.39% of Xinjiang' s total), with a regional GDP of 412.712 billion yuan (29.9% of Xinjiang' s total). Total water resources amount to 43.077 billion m^3, yielding a per capita water resource of 3604.26 $m^3 \cdot person^{-1}$, indicating relatively abundant overall water resources. However, water resource development and utilization has reached 75.78%, representing an over-exploitation state that will struggle to meet future economic development demands.

2.2 Data Sources Data for per capita water resources, urban registered unemployment rate, afforestation area, days with air quality reaching or exceeding Grade II, water supply modulus, and per capita water consumption were obtained from the *Xinjiang Yearbook* (2006-2021). Surface water resource proportion, groundwater development and utilization degree, primary industry water consumption, urban average rainfall, and residential domestic water data were primarily sourced from regional *Water Resources Bulletins* (2005-2020). Per capita GDP, rural electricity consumption, industrial output value, tertiary industry proportion, animal husbandry output value, and total retail sales of consumer goods were obtained from regional *National Economic and Social Development Statistical Bulletins* (2005-2020). Ecological environment water consumption, urban per capita park green space area, fertilizer application amount, soil erosion control area, urban waste treatment rate, and urban sewage treatment rate data were sourced from the *China Urban Construction Statistical Yearbook* (2006-2021). Missing data for individual indicators were interpolated.

2.3 Evaluation System Construction Based on existing research, water resource carrying capacity positively correlates with water resource reserves. Considering southern Xinjiang' s arid climate and relatively backward water resource utilization and treatment facilities, the evaluation system comprises 24 indicators across three subsystems:

Water Resources Subsystem: Selected from four dimensions—resource reserves, development/utilization, allocation, and efficiency—including per capita water resources, surface water resource proportion, etc.

Socioeconomic Subsystem: Selected based on southern Xinjiang' s economic model, living conditions, and industrial development status, including per capita GDP, urban registered unemployment rate, etc.

Ecological Environment Subsystem: Considering the fragile ecological foundation and focusing on human transformation and governance efforts, indicators reflecting environmental governance intensity, effectiveness, and pressure were selected.

The complete evaluation index system is presented in .

2.4 Entropy Weight-TOPSIS Model Based on Panel Data Entropy weight method is an objective weighting approach that determines indicator weights based on data dispersion degree, objectively reflecting indicator differences. This study employs panel data-based entropy weight method to calculate evaluation system weights for southern Xinjiang' s water resource carrying capacity.

Calculation Steps:

1) **Data Standardization:**
Indicators are classified as positive or negative. The range method eliminates dimensional effects:

For positive indicators:

$$A_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}$$

For negative indicators:

$$A_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}$$

where x_{ij} is the initial value of indicator j for sample i; A_{ij} is the standardized value; $x_j^{\max}$ and $x_j^{\min}$ are maximum and minimum values; $i = 1, ..., m$; $j = 1, ..., n$; m and n are sample and indicator numbers respectively.

2) **Entropy Value Calculation:**

$$p_{ij} = \frac{A_{ij}}{\sum_{i=1}^{m} A_{ij}}$$

$$e_j = -\frac{1}{\ln(v)} \sum_{i=1}^{m} p_{ij} \ln(p_{ij})$$

where p_{ij} is characteristic proportion, e_j is information entropy, v is study years.

3) **Weight Calculation:**

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}$$

TOPSIS Model:
This technique for order preference by similarity to ideal solution evaluates alternatives by calculating distances from positive and negative ideal solutions. Larger closeness coefficients indicate better performance. Detailed calculations follow Yang Liangjie et al. [17].

2.5 Coupling Coordination Model The coupling coordination model analyzes coordinated development levels. The coupling coordination degree D is calculated as:

$$D = \sqrt{C \times T}$$

$$C = \frac{3\sqrt[3]{V_1 V_2 V_3}}{V_1 + V_2 + V_3}$$

$$T = \alpha V_1 + \beta V_2 + \gamma V_3$$

where D is coupling coordination degree; C is coupling degree (0-1, higher values indicate better coordination); T is comprehensive coordination index; V_1, V_2, V_3 are subsystem self-evaluation values; α, β, γ are coefficients. Given equal importance among subsystems, $\alpha = \beta = \gamma = 1/3$.

Coupling coordination classification follows established research [25,36] as shown in .

3. Results Analysis

3.1 Water Resource Carrying Capacity Index Weight Analysis Indicator weights for southern Xinjiang' s water resources-socioeconomic-ecological environment system were calculated using formula (3). Results show the socioeconomic subsystem carries the greatest weight (0.423), followed by ecological environment (0.314) and water resources (0.263). Within the socioeconomic subsystem, industrial output value (0.089), per capita GDP (0.081), animal husbandry output value (0.076), and total retail sales (0.062) significantly influence comprehensive development levels. The ecological environment subsystem' s substantial weight indicates its importance in improving water resource development. Within water resources, per capita water resources (0.071) shows greatest influence, while residential domestic water consumption (0.012) has minimal impact.

3.2 Water Resource Carrying Capacity Analysis The entropy weight-TOPSIS model yielded comprehensive evaluation values for water resource carrying capacity and subsystems from 2005-2020 ([Figure 1: see original paper]). Bayingol shows relatively good but highly fluctuating carrying capacity, declining from 2005-2010 (minimum 0.341 in 2010), rising to maximum 0.515 in 2015, with recent fluctuations diminishing and showing upward trends. Aksu and Kashgar demonstrate fluctuating upward trends with similar growth magnitudes, both exceeding 40% increase by 2020. Kizilsu and Hotan show initial fluctuating declines followed by gradual recovery, with Hotan experiencing particularly large fluctuations. Kizilsu' s complex geography and weak economic foundation contribute to slower development.

3.3 Coupling Coordination Analysis

3.3.1 Temporal Characteristics Coupling degree C, coordination index T, and coordination degree D were calculated for five prefectures ([Figure 2: see original paper], [Figure 3: see original paper]). Overall, southern Xinjiang' s water-socioeconomic-ecological environment system maintains high coupling but low coordination (0.2-0.5), indicating mild to moderate 失调衰退型 with poor subsystem correlation. Bayingol achieved the highest coordination, rising from mild to endangered 失调衰退型. The other four prefectures progressed from moderate to mild 失调衰退型.

Based on subsystem evaluation values, Bayingol, Aksu, and Kashgar are water resources lagging types, where socioeconomic and ecological development pressure water resources. Kizilsu shows socioeconomic-ecological environment interaction lagging type, transitioning from socioeconomic lag (2005-2015) to ecological environment lag (post-2015) as industrial development accelerated. Hotan belongs to socioeconomic lagging type due to slow economic growth.

Temporal analysis reveals: 2005—All prefectures except Bayingol (mild 失调) were moderate 失调; 2010—Status unchanged but coordination improved; 2015—Significant advancement: Bayingol reached endangered 失调, others became mild 失调; 2020—Levels maintained with further improvements except Kizilsu.

3.3.2 Spatial Distribution Characteristics Spatial distribution maps generated using ArcGIS ([Figure 4: see original paper]) show strong geographical correspondence. Eastern Bayingol exhibits the best coordination. Central Aksu and Hotan, plus western Kizilsu and Kashgar, show lower levels. Kizilsu' s western border location and complex geography result in slower improvement, while Aksu, Kashgar, and Hotan display similar stable growth rates.

4. Discussion

This study' s evaluation of water resource carrying capacity and subsystem coupling coordination reveals trends consistent with Wei Xingru' s research on southern Xinjiang' s five prefectures. The low carrying capacity stems from fragile ecology, poor resource endowment, and infrastructure/technology constraints during socioeconomic development. Recent national support policies ("Belt and Road," poverty alleviation, land policies) have accelerated infrastructure development, industrial upgrading, and resource efficiency, driving upward trends in carrying capacity.

Compared with Wei Xingru' s system dynamics model, this study' s three-dimensional indicator system and coupling coordination model more clearly reflect interrelationships among water resources, socioeconomic development, and ecological environment, as demonstrated in studies of Hunan Province, the Yangtze River midstream urban agglomeration, and the Yellow River Basin. However, data limitations prevented inclusion of more comprehensive indicators such as animal husbandry water consumption and industrial sewage discharge. Future research should further refine the indicator system to enhance result accuracy and policy relevance.

5. Conclusion

1) Southern Xinjiang' s water resource carrying capacity is generally low. Bayingol shows relatively good but highly fluctuating capacity. Aksu and Kashgar demonstrate fluctuating upward trends with over 40% growth by 2020. Kizilsu and Hotan exhibit initial declines followed by gradual recovery, with Hotan showing large fluctuations.

2) From 2005-2020, the water-socioeconomic-ecological environment system remained in low-level coupling stage with poor subsystem correlation. By 2020, coordination transitioned from serious to basic 不协调, showing upward potential. Bayingol achieved the best coordination level (endangered 失调衰退型), while others reached mild 失调衰退型. Subsystem lag analysis identifies: water resources lagging type in Bayingol, Aksu, and Kashgar; socioeconomic-ecological environment interaction lagging type in Kizilsu; and socioeconomic lagging type in Hotan.

3) Spatially, coupling coordination shows strong geographical correspondence, with eastern regions outperforming central and western areas. Bayingol maintains the best coordination level. Among other regions, Kizilsu' s western border location and complex geography cause slower improvement, while Aksu, Kashgar, and Hotan exhibit similar stable growth rates.

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