Postprint: Coordination Analysis of Water Resources Utilization in the Five Northwestern Provinces and Autonomous Regions of China

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Abstract

The coordinated utilization of water resources is the foremost challenge for the economic, social, and ecological sustainable development of the five northwestern provinces and autonomous regions of China. Employing synergy analysis methods and a coupling coordination degree model, this study analyzes the regional synergy and coupling coordination degree between water resource utilization rate and ecological water use rate in the five northwestern provinces and autonomous regions of China—Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The results indicate: (1) The water resource utilization rates and ecological water use rates in the five northwestern provinces and autonomous regions exhibit homogeneity of variance, with no significant regional differences between any two provinces or autonomous regions, while demonstrating regional synergy within all five provinces and autonomous regions. (2) The fluctuations in ecological water use rate in the five northwestern provinces and autonomous regions primarily depend on whether local agricultural water management policies are timely and sustainably effective. (3) Among the five northwestern provinces and autonomous regions, except for Xinjiang which is at the "barely coordinated" level, the coupling coordination degree between water resource utilization rate and ecological water use rate in the other four provinces and autonomous regions is extremely low, generally far from the "coordination pole" and biased toward the "disharmony pole." (4) The rise and fall of coupling coordination degree levels in the five northwestern provinces and autonomous regions exhibits a positive correlation with the level of ecological water use rate in each province or autonomous region. (5) In 2018, the status levels of "mild disharmony" in Shaanxi, "verging on disharmony" in Gansu, and "barely coordinated" in Xinjiang were relatively easy to adjust and improve, with the key being to increase their ecological water use rates, while the status levels of "severe disharmony" in Qinghai and "moderate disharmony" in Ningxia must be given high priority and comprehensively reversed to prevent further deterioration.

Full Text

Coordination of Water Resources Utilization in the Five Northwestern Provinces of China

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Abstract

The coordination of water resource utilization represents the foremost challenge for sustainable economic, social, and ecological development in the five northwestern provinces of China. Employing synergy analysis methods and a coupling coordination degree model, this study examines the regional synergy and coupling coordination between water resources utilization ratio and ecological water use ratio in Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The results indicate: (1) The variances of water resources utilization ratio and ecological water use ratio are homogeneous across the five provinces, with no statistically significant regional differences between any two provinces, demonstrating regional synergy within each province. (2) Fluctuations in the ecological water use ratio across the five provinces primarily depend on the timeliness and sustained effectiveness of local agricultural water management policies. (3) Except for Xinjiang, which reaches the "barely coordinated" level, the coupling coordination degrees between water resources utilization ratio and ecological water use ratio in the other four provinces are extremely low, generally deviating far from the "coordination pole" and leaning toward the "imbalance pole." (4) The rise and fall of coupling coordination degree levels in each province correlate positively with the ecological water use ratio. (5) In 2018, the status levels of "mild imbalance" in Shaanxi, "verge of imbalance" in Gansu, and "barely coordinated" in Xinjiang are relatively amenable to improvement through enhanced ecological water use ratios, whereas the "severe imbalance" in Qinghai and "moderate imbalance" in Ningxia demand urgent comprehensive intervention to prevent further deterioration.

Keywords: water resources utilization; coupling coordination; optimizing water use structure; ecological water use; five northwestern provinces of China

1. Introduction

China faces severe water scarcity, and the five northwestern provinces predominantly consist of arid and semi-arid regions where water shortages constrain local economic development and ecological improvement. Water utilization typically comprises four categories: agricultural, industrial, domestic, and ecological water use. This study defines agricultural water use as including both irrigation and livestock water consumption, while ecological water use primarily refers to artificial water replenishment for rivers, lakes, wetlands, and urban environments. The total water consumption in the five northwestern provinces reaches

848×10^{3} units, accounting for approximately 14.3% of the national total. As the starting segment of the Silk Road Economic Belt within China, the regional and typological coordination of water resources in this area is critical not only for local sustainable development but also for the successful implementation of this national strategy.

Scholars have examined water resource sustainability in arid and semi-arid regions from various perspectives. Shirmohammadi et al. demonstrated through scenario analysis that reducing water withdrawals can significantly expand rain-fed agriculture in these areas. Trasviña-Carrillo et al. employed groundwater modeling to show that population growth-driven groundwater extraction leads to continued aquifer vulnerability and unsustainable water use. Haghighi et al. identified unsustainability syndromes in arid regions, noting that large-scale conversion from rain-fed to irrigated agriculture exerts tremendous pressure on regional water resources, representing a primary cause of agricultural unsustainability. At the county level, grid-based agricultural management proves effective for improving water and land resource efficiency in northwestern arid regions. Jia Shaofeng et al. traced the 40% threshold for water resources development and utilization ratio, recommending it as the minimum ecological flow for rivers in northwestern arid areas. Zhang Zhenlong et al. analyzed water use efficiency and its influencing factors, concluding that efficiency levels in northwestern arid regions show a divergent trend, with regional disparities expected to widen further.

Li Wanming et al. examined the matching between water resource utilization and economic factors, finding poor matches in Xinjiang and Shaanxi, moderate alignment in Gansu, and relatively good correspondence in Ningxia and Qinghai. Xia Weijing et al., using watershed-based evaluation units, analyzed water resource carrying capacity in Shaanxi Province, revealing mismatches between water resource distribution and productivity or population centers, while highlighting the critical role of inter-basin water transfer projects. Li Fei et al. analyzed the temporal and spatial characteristics of water resource ecological footprint and carrying capacity in Gansu, concluding that despite ecological deficits, improving water use efficiency has alleviated supply-demand contradictions, with agricultural water use—showing a declining trend—constituting the largest footprint account. Huang Xiaorong employed multi-objective optimization modeling to develop water allocation schemes for Ningxia under different hydrological conditions, prioritizing domestic water use while ensuring industrial needs and appropriate ecological water requirements. Lin Qing emphasized that water ecological civilization construction is fundamental to Xinjiang' s high-quality development, focusing on resolving excessive water consumption and severe pollution. Meng Jiangli proposed establishing response relationships between water resource development schemes and ecological protection targets by coordinating upstream, midstream, and downstream water use in the Baiyang River Basin. Tian Yuelin studied water-efficient utilization systems in industrial parks across northwestern arid regions, proposing a "graded treatment and multi-level reuse" framework adapted to local resource endowments.

Despite these contributions, comprehensive analyses integrating agricultural, industrial, domestic, and ecological water use types to examine the spatiotemporal coordination between regional water resource utilization and ecological water use remain scarce. This study investigates the regional synergy and coupling coordination between water resource utilization indicators and ecological water use indicators across the five northwestern provinces, aiming to provide insights for optimizing water use structure and promoting sustainable water resource utilization.

2. Data and Methods

2.1 Data Sources

Annual data from 2003 to 2018 were obtained from the *China Statistical Yearbook*, *China Environmental Statistical Yearbook*, and provincial statistical yearbooks of Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The dataset includes total water resources, total water consumption, agricultural water use, industrial water use, domestic water use, and ecological water use for both national and provincial scales.

2.2 Methodology

2.2.1 Range Standardization To eliminate annual data fluctuations, enhance comparability among provinces, and improve the accuracy of regional difference analysis, range standardization was applied to water resources utilization ratio and ecological water use ratio based on their maximum and minimum values across the five provinces. The calculation formula is:

$$X_i' = \frac{X_i - \min(X)}{\max(X) - \min(X)} \times 100\%$$

where $i = 2003, 2004, \dots, 2018$ represents each year; X_i is the original indicator value for year i; X_i' is the standardized value; and $\max(X)$ and $\min(X)$ are the maximum and minimum values of the indicator during the study period.

2.2.2 Synergy Analysis Synergy refers to the mutual cooperation and interaction between two or more systems or system elements, representing a harmonious and positive matching relationship. Under China' s current water resource development and water ecological civilization construction context, water resource utilization indicators and ecological water use indicators exhibit a mutually promoting relationship with inherent synergy. SPSS 22.0 software was used to conduct one-way ANOVA on these indicators across the five provinces to reveal their regional synergy characteristics.

2.2.3 Coupling Coordination Degree Model The coupling coordination degree model, adapted from physics' capacity coupling coefficient model, was employed to analyze the coordination between water resource utilization and ecological water use indicators within each province. The model formulas are:

$$D_j = \sqrt{C_j \times T_j}$$

$$C_j = \frac{CP_j \times EP_j}{\left[(CP_j + EP_j)/2\right]^2}$$

$$T_j = \alpha \times CP_j + \beta \times EP_j$$

$$CP_j = \frac{CW_j}{TW_j} \times 100\%$$

$$EP_j = \frac{EW_j}{TW_j} \times 100\%$$

where D_j is the coupling coordination degree for region j ($j = 1, 2, \dots, 5$ representing Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang), ranging [0, 1]; C_j is the coupling degree, also ranging [0, 1]; T_j is the comprehensive benefit evaluation index, ranging [0, 1]. All three are positive indicators of regional development level. CP_j and EP_j represent the standardized values of water resources utilization ratio and ecological water use ratio, respectively. TW_j, CW_j, and EW_j denote total water resources, total water consumption, and ecological water consumption for region j. Parameters α and β are non-negative coefficients satisfying $\alpha + \beta = 1$; based on existing research and the four main water use types considered, $\alpha = \beta = 0.5$ was selected. Table 1 presents the evaluation criteria for coupling coordination degree.

Table 1. Evaluation standard of coupling coordination degree

Coupling coordination degree (D_j)	Coordination level	Coupling coordination degree (D_j)	Coordination level
[0.89, 1.00]	Premium coordination	[0.39, 0.49)	Moderate imbalance
[0.79, 0.89)	Good coordination	[0.29, 0.39)	Mild imbalance
[0.69, 0.79)	Basic coordination	[0.19, 0.29)	Verge of imbalance
[0.59, 0.69)	Primary coordination	[0.09, 0.19)	Severe imbalance

Coupling coordination degree (D_j)	Coordination level	Coupling coordination degree (D_j)	Coordination level
[0.49, 0.59)	Barely coordination	[0.00, 0.09)	Extreme imbalance

3. Results

3.1 Regional Synergy Analysis

3.1.1 Homogeneity of Variance Test Results Levene's test results (Table 2) indicate that at the 0.05 significance level, the null hypothesis should be accepted: the variances of water resources utilization ratio and ecological water use ratio are homogeneous across the five northwestern provinces. This implies no significant regional differences in these two indicators across the study area.

Table 2. Homogeneous test results of CP_j and EP_j in the study area from 2003 to 2018

Variance homogeneity test	Between-group df	Within-group df	Significance probability
Water resources utilization ratio	4	75	0.999
Ecological water use ratio	4	75	0.999

3.1.2 Regional Synergy Analysis Results Under the premise of variance homogeneity, Duncan' s multiple range test results (Table 3) show that water resources utilization ratio and ecological water use ratio across all pairwise province comparisons fall into the same subset, indicating no significant regional differences. Consequently, these two indicators exhibit regional synergy within Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

Table 3. Variance analysis results of CP_j and EP_j in the study area from 2003 to 2018

Variance analysis method	Significance level 0.05 test results
Water resources utilization ratio subsets	Cochran' s test significance probability: 1.000Duncan' s test significance probability: 1.000
Ecological water use ratio subsets	Cochran' s test significance probability: 1.000Duncan' s test significance probability: 1.000

Note: Sample size estimated using harmonic mean of 16 observations per group. Groups 1-5 represent Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

3.1.3 Water Use Structure Comparison A comparison of water use structures between the five provinces and national averages in 2010 and 2018 reveals that agricultural water use dominates and remains the most stable category across provinces, consistently exceeding national levels. While all provinces except Gansu reduced agricultural water proportions between 2010 and 2018, Xinjiang' s share remained highest at over 90%. Industrial and domestic water use proportions are secondary. Industrial water use decreased in Gansu and Qinghai (aligning with national trends) but increased slightly in the other three provinces. Domestic water use proportions increased modestly across all provinces. Ecological water use ratios are the smallest (ranging only 1-5%) but show consistent upward trends both nationally and provincially.

3.1.4 Temporal Dynamics of Ecological Water Use Ratio Figure 2 illustrates the annual dynamics of ecological water use ratios from 2003 to 2018. The national average generally falls between the provincial values. Shaanxi shows an inverted "V" pattern with an overall increasing trend except for a 2014 decline. Gansu exhibits minor fluctuations before a sharp rise after 2014. Qinghai' s pattern resembles an "N" shape with initial increases, subsequent decreases, and final recovery. Ningxia demonstrates the steadiest increase among the five provinces. Xinjiang shows the most volatile pattern: significant increases during 2003-2010, a notable decline during 2011-2014, and relative stability thereafter, though consistently above other provinces and the national average. Overall, ecological water use ratios across the five provinces and nationally remained stable with a steady upward trend from 2015 to 2018, gradually yielding "ecological dividends."

3.2 Coupling Coordination Degree Between Water Resources Utilization Ratio and Ecological Water Use Ratio

Applying the coupling coordination degree model to 2003-2018 data reveals consistently low coordination levels across the five provinces (Table 4). Based on the criteria in Table 1, Shaanxi experienced "severe imbalance" in 2003, "moderate imbalance" during 2004-2009, and "mild imbalance" from 2010-2018. Gansu showed "moderate imbalance" in 2003-2004 and 2007-2009, "mild imbalance" during 2005-2006 and 2010-2017, and reached "verge of imbalance" in 2018. Qinghai exhibited the lowest coordination: "moderate imbalance" only in 2003, and "severe imbalance" throughout all other years. Ningxia progressed from "extreme imbalance" in 2003 to "severe imbalance" during 2004-2009, "moderate imbalance" during 2010-2017, and achieved "mild imbalance" in 2018. Xinjiang demonstrated the highest coordination levels, reaching "barely coordinated" during 2003-2009 and 2014-2016, maintaining "verge of imbalance" during 2010-2013 and 2017-2018, and showing "mild imbalance" only in 2010.

Table 4. Coordination degree between water resources utilization ratio and ecological water use ratio of the five provinces from 2003 to 2018

Year	Shaanxi	Gansu	Qinghai	Ningxia	Xinjiang
2003	0.2867	0.2963	0.2963	0.0833	0.5037
2004	0.2963	0.2963	0.2867	0.2867	0.5130
2005	0.2963	0.3130	0.2867	0.2963	0.5222
2006	0.3130	0.3130	0.2867	0.2963	0.5315
2007	0.3130	0.2963	0.2867	0.2867	0.5407
2008	0.3130	0.2963	0.2867	0.2867	0.5500
2009	0.3130	0.2963	0.2867	0.2867	0.5593
2010	0.3222	0.3222	0.2867	0.2963	0.3222
2011	0.3315	0.3315	0.2867	0.2963	0.5685
2012	0.3407	0.3407	0.2867	0.2963	0.5778
2013	0.3500	0.3500	0.2867	0.2963	0.5870
2014	0.3593	0.3593	0.2867	0.2963	0.5963
2015	0.3685	0.3685	0.2867	0.3056	0.6056
2016	0.3778	0.3778	0.2867	0.3148	0.6148
2017	0.3870	0.3870	0.2867	0.3241	0.4333
2018	0.3963	0.4056	0.2867	0.3333	0.4426

Table 5. Grade distributions of coordination degree between water resources utilization ratio and ecological water use ratio of the five provinces from 2003 to 2018

Coordination level	Shaanxi	Gansu	Qinghai	Ningxia	Xinjiang
Premium coordination	0	0	0	0	0
Good coordination	0	0	0	0	0
Basic coordination	0	0	0	0	0
Primary coordination	0	0	0	0	0
Barely coordination	0	0	0	0	13
Verge of imbalance	0	1	0	0	3
Mild imbalance	9	6	0	1	1
Moderate imbalance	6	2	1	9	0
Severe imbalance	0	6	15	5	0
Extreme imbalance	0	0	0	1	0

4. Conclusions

Based on the analysis of regional synergy and coupling coordination degree between water resources utilization ratio and ecological water use ratio in Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang from 2003 to 2018, the main conclusions are:

1. **Regional synergy exists across the five provinces.** No significant regional differences were found in water resources utilization ratio or ecological water use ratio between any two provinces. The two indicators

demonstrate positive matching relationships and regional synergy within each province.

2. **Agricultural water use dominates but shows improving efficiency.** Agricultural water consumption accounts for the largest proportion and significantly exceeds national levels, indicating substantial potential for efficiency improvements and water conservation, particularly in Gansu and Xinjiang through advanced irrigation and livestock water-saving practices. The declining industrial water use proportions in Gansu and Qinghai reflect successful water efficiency gains and circular economy promotion. Meanwhile, domestic water use proportions and ecological water use ratios show stable upward trends, demonstrating improved prioritization of human needs and progressive implementation of the "lucid waters and lush mountains are invaluable assets" concept.

3. **Ecological water use ratio fluctuations reflect policy effectiveness.** The rise and fall of ecological water use ratios depend largely on the timeliness and sustained effectiveness of local agricultural water management policies. Implementing strict water resource management systems that prohibit encroachment on ecological water allocations, combined with improved agricultural water efficiency through widespread adoption of water-saving irrigation, has enabled ecological water use ratios to recover favorably. From 2015 to 2018, ecological water use ratios across the five provinces and nationally showed stable, steady increases, gradually generating "ecological dividends."

4. **Coupling coordination degrees remain low but correlate with ecological water use.** The coupling coordination degrees between water resources utilization ratio and ecological water use ratio are very low across the five provinces, generally distant from the "coordination pole" and biased toward the "imbalance pole," indicating a long road ahead for coordinated water use. However, the coupling coordination level in each province correlates positively with its ecological water use ratio—higher coordination corresponds to higher ecological water use efficiency. Xinjiang has entered a "coordinated" state, while Shaanxi shows gradually improving trends, reflecting these provinces' success in leveraging local resource advantages for green industries like ecological tourism and releasing regional "ecological dividends."

5. **Provincial disparities require targeted interventions.** In 2018, the status levels of "mild imbalance" in Shaanxi, "verge of imbalance" in Gansu, and "barely coordinated" in Xinjiang are relatively adjustable through increased ecological water use ratios. In contrast, the "severe imbalance" in Qinghai and "moderate imbalance" in Ningxia require urgent, comprehensive measures to reverse these trends and prevent further deterioration.

5. Recommendations

Given the overall "imbalance" status of coupling coordination degrees and the positive development trends in Xinjiang and Shaanxi, implementing national water ecological civilization construction requirements and intensifying the *National Water Conservation Action Plan* are imperative.

1. **Promote sustainable water use through public engagement.** Focus on the long-term goal of sustainable water resources utilization in the five northwestern provinces by educating households about water efficiency and ecological protection. Strengthen water policy advocacy to enhance public water conservation awareness and literacy, ensuring that Xi Jinping's ecological civilization thought—centered on the "Two Mountains" theory—becomes widely understood, deeply internalized, and actively practiced.

2. **Target agricultural water use as the key intervention point.** Address severe waste in irrigation and other agricultural water uses by improving crop irrigation technical efficiency, expanding water-saving irrigation coverage, and enhancing livestock water efficiency. Integrate modern information technologies to advance metering infrastructure, enabling precise water measurement, quota-based pricing, total quantity control, and quantitative management in agricultural water use.

3. **Implement efficiency evaluation and ecological compensation mechanisms.** Utilize water use efficiency evaluation results across all water use types and establish robust ecological compensation mechanisms for water resources utilization with comprehensive legal safeguards. Enforce strict industrial and agricultural water use evaluation standards and regulatory measures to continuously drive green transformation of economic development patterns.

4. **Develop unconventional water resources.** On the foundation of optimizing conventional water allocation, maximize the development and utilization of unconventional water sources—including reclaimed water, brackish water, mine water, rainwater, and atmospheric water—to ensure adequate ecological water supplies in multiple ways. This will continuously improve the coupling coordination degree between water resources utilization ratio and ecological water use ratio, optimize the four-category water use structure, and ensure ecological water use effectively safeguards sustainable water resources utilization across the five northwestern provinces.

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Figures

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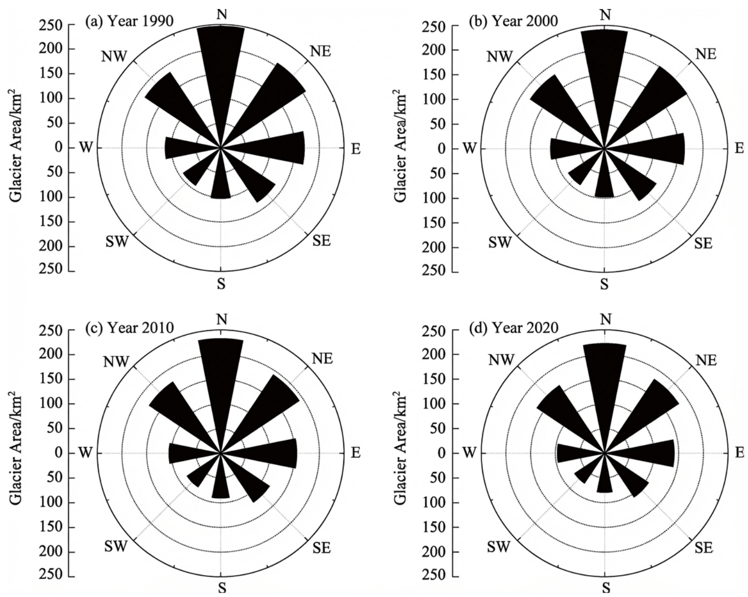

Figure 1: Figure 2