# Study and Prediction of Coupling Coordination Degree among Water Resources, Socioeconomic Development, and Ecological Environment: A Case Study of the Inner Mongolia Section of the Yellow River Basin (Postprint)

**Authors:** Meng Qingshuai, Gong Yu, Liu Xiaoyan, Tong Xin, Wang Dongmin, Xie Guoying, Liu Tingxi

**Date:** 2025-04-08T00:00:00+00:00

## Abstract

With the rapid development of economy and society, the competition between human activities and the natural environment has significantly intensified, making the choice between social development and environmental protection an important issue. First, this paper constructs a coupling coordination degree model for the water resources-socioeconomic-ecological environment composite system to clarify the coordinated development status of the system in the Inner Mongolia section of the Yellow River Basin from 1998 to 2022. Second, it uses an improved LSTM (Long Short-Term Memory) model to predict the system' s development over the next 5 years based on four comprehensive regulation schemes. The results show that: (1) The evaluation index distribution intervals of the water resources, socioeconomic, and ecological environment subsystems in the various leagues and cities of the Inner Mongolia section of the Yellow River Basin are [0.47~0.57], [0.47~0.87], and [0.42~0.58], respectively, indicating that the overall coordination status of the regional water resources and ecological environment subsystems is at a medium level, while the socioeconomic subsystem, although relatively high, still has room for development; (2) The coupling coordination degree of the water resources-socioeconomic-ecological environment system in the various leagues and cities of the Inner Mongolia section of the Yellow River Basin shows a gradual upward trend between 0.67~0.80, with an overall change amplitude of 19%; (3) Through predictions of future scenarios, it is found that the joint regulation of water resources-socioeconomic factors yields the greatest improvement for the three leagues of Alxa, Bayannur, and Ulanqab; the joint improvement of socioeconomic-ecological environment factors yields the greatest improvement for Wuhai City; and the joint regulation of water resources-ecological environment factors yields the greatest improvement for Baotou City, Hohhot City, and Ordos City.

## Full Text

## Preamble

**Arid Zone Research** Vol. 42 No. 4 Apr. 2025
DOI:10.13866/j.azr.2025.04.10 CSTR:32277.14.AZR.20250410

### Research and Prediction of Coupling Coordination Degree Relationships in Water Resources-Socioeconomic-Ecological Environment Systems: A Case Study of the Inner Mongolia Section in the Yellow River Basin

MENG Qingshuai[1], GONG Yu[1,2,3,4], LIU Xiaoyan[1,2,3,4], TONG Xin[1,2,3,4], WANG Dongmin[5], XIE Guoying[6], LIU Tingxi[1,2,3,4]

[1]Water Conservancy and Civil Engineering College, Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China
[2]State Key Laboratory of Water Engineering Ecology and Environment in Arid Area, Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China
[3]Inner Mongolia Key Laboratory of Ecohydrology and High Efficient Utilization of Water Resources, Hohhot 010018, Inner Mongolia, China
[4]Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in Inner Mongolia Section of the Yellow River Basin, Hohhot 010018, Inner Mongolia, China
[5]Water Conservancy Bureau of Aohan Banner, Chifeng 024300, Inner Mongolia, China
[6]Development Center for Water Conservancy in Inner Mongolia Autonomous Region, Hohhot 010010, Inner Mongolia, China

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## Abstract

With rapid socioeconomic development, competition between human activities and the natural environment has intensified significantly, making the trade-off between socioeconomic progress and environmental protection a critical issue. This study first constructs a coupling coordination degree model for a water resources-socioeconomic-ecological environment composite system to clarify the coordinated development status of the Inner Mongolia section in the Yellow River Basin from 1998 to 2022. Second, an improved Long Short-Term Memory (LSTM) model is employed to predict the system' s development trends over the next five years under four integrated regulation scenarios. The evaluation index distribution intervals for water resources, socioeconomic, and ecological environment subsystems are [0.47~0.57], [0.47~0.87], and [0.42~0.58], respectively. The results indicate: (1) The water resources and ecological environment subsystems in the Inner Mongolia section of the Yellow River Basin maintain a moderate coordination level overall, while the socioeconomic subsystem shows relatively higher development potential but still has room for improvement. (2) The coupling coordination degree of the composite system across the seven league/cities shows a gradual upward trend between 0.67~0.80, with an overall variation amplitude of 19%. (3) Future scenario predictions reveal that joint regulation of water resources and socioeconomic factors yields the greatest improvement in Alxa League, Bayannur City, and Ulanqab City; Wuhai City benefits most from joint socioeconomic-ecological environment regulation; and Baotou City, Hohhot City, and Ordos City achieve optimal improvement through joint water resources-ecological environment regulation.

**Keywords:** coupling coordination degree; spatiotemporal distribution characteristics; improved LSTM; Inner Mongolia section of the Yellow River Basin

## Introduction

Society constitutes a complex system wherein resources, ecology, society, and economy form multiple intrinsic coupling relationships. Evaluation of regional development has shifted from unidimensional assessment of development level to holistic balanced development evaluation based on both coordination and development levels. Consequently, the coupling coordination degree, which assesses the matching degree and coordination of composite systems during co-development processes, has become an effective evaluation tool.

Numerous scholars have conducted extensive research on coupling coordination development of regional complex systems. For instance, previous studies have constructed industrial water price indicator systems and employed comprehensive evaluation methods, coupling degree models, and coupling coordination degree models to analyze the water resources-socioeconomic-ecological environment system in the Yellow River Basin. Other research has utilized coupling coordination models and panel vector autoregression (PVAR) models to explore the dynamic interactions within water resources carrying capacity systems from the perspectives of water resources, society, economy, and ecological environment. However, while existing studies have established various composite evaluation indicator systems and applied coupling coordination degree models for multi-angle assessments across different regions, few have reported on future development predictions and simulations.

This study analyzes regional coupling coordination relationships while improving the LSTM model. By employing cross-input data methods to mitigate the impact of limited data volume on prediction accuracy and incorporating indicator balance relationships into predictions, the model' s rationality and practicality are further enhanced. This improved model is then applied to predict future coupling coordination degree development across seven league/cities in the Inner Mongolia section of the Yellow River Basin under different scenarios.

## 1.1 Study Area and Data Sources

The Inner Mongolia section of the Yellow River Basin is located in the upper half of the Yellow River' s "Ji" character bend, flowing through seven administrative units: Hohhot City, Baotou City, Wuhai City, Ordos City, Bayannur City, Ulanqab City, and Alxa League, with geographical coordinates of 97°13 ~114°48 E and 37°36 ~43°21 N. The region' s economic development, ecological environment, and water resources present distinct characteristics and challenges. Economically, the area relies primarily on agriculture and animal husbandry, which contribute significantly to regional GDP, while industry and services are gradually diversifying the economic structure. Ecologically, although the region possesses extensive grassland areas, approximately one-third has experienced degradation, threatening biodiversity and environmental quality. Regarding water resources, approximately 70% of farmland depends on Yellow River irrigation, yet overexploitation and pollution have caused water quality deterioration, posing challenges to sustainable development.

Data were collected at the league/city level, encompassing social, economic, water resources, and ecological data. The majority of data were obtained from the *Inner Mongolia Water Resources Bulletin*, *Inner Mongolia Environmental Status Bulletin*, and statistical yearbooks of each league/city (1998-2022). Vegetation coverage data were derived from the Google Earth Engine platform using MODIS MOD13Q1 NDVI data, cropped and calculated according to each league/city' s administrative vector boundaries. Minimal missing data (e.g., sewage treatment rates in 1998, industrial wastewater discharge in 2002) were supplemented using trend extrapolation.

## 1.2 Research Methods

The water resources-socioeconomic-ecological environment coupling system represents a multi-dimensional complex system that integrates the interactions and interdependencies among water resources management, socioeconomic development, and ecological environment balance. In this system, water resource circulation and utilization directly influence socioeconomic activities while being closely related to natural ecosystem health. The subsystems exhibit complex and multifaceted relationships.

### 1.2.1 Indicator System Construction

Based on previous indicator construction experience, a comprehensive evaluation indicator system for the water resources-socioeconomic-ecological environment composite system was established (Table 1). Following principles of comprehensiveness, accessibility, relevance, and scientific rigor, the system comprises 6 water resources indicators, 8 socioeconomic indicators, and 6 ecological environment indicators. Water resources indicators cover supply and utilization dimensions, reflecting regional water supply capacity, use efficiency, and natural water cycle characteristics. Socioeconomic indicators include social water use structure and economic development dimensions, revealing the interaction between regional socioeconomic activities and water resources. Ecological environment indicators encompass ecological protection and environmental pollution dimensions, measuring ecosystem health and sustainability.

### 1.2.2 Indicator Weight Determination

The entropy weight method objectively reflects indicator importance by calculating information entropy, avoiding subjective interference. The specific calculation steps are:

1) Construct an original data matrix with $n$ samples and $m$ evaluation indicators, normalized to obtain judgment matrix $X$:

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{pmatrix}$$

2) Calculate the entropy value *H_j* for each indicator based on the judgment matrix:

$$H_j = -k \sum_{i=1}^{n} P_{ij} \ln P_{ij}$$

where $k$ is a constant ($k = 1/\ln n$) to ensure entropy values range between [0,1]. If *P_{ij}* $= 0$, define *P_{ij}* ln *P_{ij}* $= 0$ to avoid numerical computation issues.

3) Calculate the entropy weight *w_{ij}* of each evaluation indicator:

$$w_{ij} = \frac{1 - H_j}{\sum_{j=1}^{m} (1 - H_j)}$$

where *w_{ij}* is the weight of the $j$-th indicator, and the sum of weights equals 1.

### 1.2.3 Coupling Coordination Model Construction

The coupling coordination degree model is an important tool for evaluating the interaction and coordinated development degree among different systems or subsystems, widely applied in integrated research on water resources management, socioeconomic development, and ecological environment protection. In studying the coupling and coordination of water resources, socioeconomic, and ecological environment subsystems, this model reveals their interactions and dependencies while assessing overall coordination, providing scientific decision-making basis for sustainable development.

Subsystem evaluation indices:

$$f(x) = \sum_{i=1}^{m} w_i x_i, \quad g(y) = \sum_{i=1}^{n} s_i y_i, \quad h(z) = \sum_{i=1}^{k} e_i z_i$$

where *f(x)*, *g(y)*, and *h(z)* represent comprehensive benefits of the subsystems; *w_i*, *s_i*, and *e_i* are indicator weights; *x_i*, *y_i*, and *z_i* are dimensionless indicator values; and *m*, *n*, *k* are the numbers of indicators in each subsystem.

Coupling degree $C$ describes the interaction intensity among subsystems, reflecting interdependence. $C$ ranges between [0,1], with high values indicating strong interaction and dependency, and low values indicating weak interaction. For the three subsystems:

$$C = 3\sqrt[3]{f(x) \cdot g(y) \cdot h(z)}/(f(x) + g(y) + h(z))$$

Comprehensive evaluation index $T$ helps identify interactions and coordination states among water resources management, socioeconomic development, and ecological environment protection:

$$T = \alpha f(x) + \beta g(y) + \gamma h(z)$$

where $\alpha$, $\beta$, and $\gamma$ are subsystem weights. This study examines all three systems simultaneously, considering them equally important ($\alpha = \beta = \gamma = 1/3$).

While coupling degree is valuable for describing basic interactions, coupling coordination degree provides more comprehensive analysis of relationship quality, coordination, and contribution to overall objectives. Coupling coordination degree $D$ considers both interaction intensity and overall coordinated development level:

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

$D$ ranges between [0,1], with high values indicating strong interaction and synergistic development, and low values indicating weak coordinated development with potential lags in certain subsystems.

### 1.2.4 Future Prediction–Based on Improved LSTM

Given limited training data and non-independence among some indicators, direct application of traditional LSTM models may produce low accuracy, overfitting, or unrealistic results. This study improves the LSTM model through cross-input data patterns for multi-dimensional feature extraction, enhancing accuracy. The loss function is modified during training by adding constraint loss terms to guide the model in learning balance relationships. During prediction, constraints are embedded to ensure outputs comply with real-world conditions.

Long Short-Term Memory (LSTM) is a special recurrent neural network (RNN) structure for processing and learning time series data. Its core components are internal "memory cells" and a series of "gates" controlling information flow, enabling selective retention or forgetting of information. A typical LSTM unit includes:

1) A "conveyor belt" cell state that propagates information through the sequence with minimal linear operations, allowing long-term information flow.
2) A forget gate that filters input (including previous predictions) and hidden states through linear transformations, selecting the most valuable information for future predictions while discarding unimportant historical data:

$$f_t = \sigma(W_f \times [h_{t-1}, x_t] + b_f)$$

where $\sigma$ is the sigmoid function, *W_f* is the weight matrix, *h_{t-1}* is the internal state information retained from the previous time step, *x_t* is current input data, and *b_f* is the bias term.

3) An input gate determining how much new information at the current time step will be added to the cell state, helping the model effectively update cell states using 25 years of training data to generate future predictions:

$$i_t = \sigma(W_i \times [h_{t-1}, x_t] + b_i)$$

$$\tilde{C}_t = \tanh(W_C \times [h_{t-1}, x_t] + b_C)$$

where *tanh* is the hyperbolic tangent function generating candidate values.

4) An output gate determining how much information from the current hidden state (LSTM unit output) will be used to predict next year' s indicator values while providing key inputs for subsequent predictions, ensuring the model can derive five-year future trends from 25 years of historical data:

$$o_t = \sigma(W_o \times [h_{t-1}, x_t] + b_o)$$

$$h_t = o_t \times \tanh(C_t)$$

### 2.1.1 Subsystem Evaluation Index Interannual Variation Analysis

Subsystem evaluation indices reflect development levels and potential. Analysis of water resources, socioeconomic, and ecological environment subsystems across seven league/cities in the Inner Mongolia Yellow River Basin section (Figure 2) reveals:

- Water resources subsystem indices range between 0.47~0.57, showing small fluctuations.
- Socioeconomic subsystem indices exhibit a clear upward trend between 0.47~0.87, demonstrating the most significant change, clearest trend, and highest development level among the three subsystems.
- Ecological environment subsystem indices range between 0.42~0.58, showing slight fluctuations.

### 2.1.2 System Comprehensive Evaluation Index T Spatiotemporal Variation Analysis

To comprehensively assess water resources-socioeconomic-ecological environment system development, typical years (2000, 2010, 2020, 2022) were selected to map spatiotemporal evolution of the comprehensive evaluation index $T$ (Figure 3). All seven league/cities show noticeable increases in $T$ values. In 2000, the Hohhot-Baotou-Ordos economic zone and Ulanqab City had lower $T$ values than western regions (Alxa League, Bayannur City, Wuhai City). However, due to differential growth rates, the spatial pattern reversed by 2022. The overall $T$ value growth interval across the basin is 0.42~0.58, with all league/cities showing fluctuating upward trends.

## 2.2 Coupling Coordination Degree Variation Analysis

From 1998 to 2022, the water resources-socioeconomic-ecological environment coupling coordination degree across seven league/cities in the Inner Mongolia Yellow River Basin section ranged between 0.67~0.80 (Figure 4). Although development speeds varied significantly among cities, the overall trend was upward year by year, increasing from primary coordination through intermediate coordination toward good coordination stage. This coordination level indicates that while water resources management, socioeconomic development, and ecological environment protection have achieved some balance, optimal coordination has not yet been reached. Specifically, rapid socioeconomic development exerts pressure on water resources and ecological environment systems, while unbalanced resource allocation and insufficient environmental protection measures constrain further coordination improvement.

### 2.3.1 Model Validation

Using 1998-2020 data as the initial training set, the model predicted 2021-2022 indicator values. Comparison between traditional and improved LSTM models (Figure 5 and Figure 6, using Hohhot as an example) demonstrates that traditional LSTM models produce information distortion when predicting with limited data, whereas the improved model shows significantly higher accuracy. The improved model maintains high precision while ensuring rationality of indicators with balance relationships (e.g., sum of water use proportions equals 100%, sum of industrial structure proportions equals 100%).

### 2.3.2 Regulation Scenarios

Considering indicator controllability and rationality, three regulation measures were proposed for each subsystem: - **Water resources regulation**: Total water consumption decreases by 2% annually; industrial water proportion decreases by 1% annually. - **Socioeconomic regulation**: Secondary industry proportion increases by 1% annually; urban population increases by 1% annually. - **Ecological environment regulation**: Ecological water use increases by 1% annually; industrial wastewater discharge decreases by 2% annually.

Four scenarios were designed: - **Scenario 1**: No regulation, maintaining normal development. - **Scenario 2**: Joint water resources-socioeconomic regulation (total water consumption ↓2%; industrial water proportion ↓1%; secondary industry proportion ↑1%; urban population ↑1%). - **Scenario 3**: Joint socioeconomic-ecological environment regulation (secondary industry proportion ↑1%; urban population ↑1%; ecological water use ↑1%; industrial wastewater discharge ↓2%). - **Scenario 4**: Joint water resources-ecological environment regulation (total water consumption ↓2%; industrial water proportion ↓1%; ecological water use ↑1%; industrial wastewater discharge ↓2%).

Predictions for each city under different scenarios (2023-2027) show (Figure 7): - **Alxa, Bayannur, Ordos, and Ulanqab** respond well to Scenarios 2 and 4, both containing water resources regulation, indicating these four league/cities must prioritize water resources management. Among them, **Alxa, Bayannur, and Ulanqab** achieve highest coordination under Scenario 2, requiring simultaneous water resources management and socioeconomic development. **Ordos** achieves best results under Scenario 4, indicating ecological construction also needs attention. - **Baotou, Hohhot, and Wuhai** show significant improvement under Scenarios 3 and 4, both containing ecological environment regulation, indicating ecological protection is the primary concern. **Baotou and Hohhot** achieve optimal coordination under Scenario 4, suggesting scientific water resources utilization and management are secondary priorities after ecological protection. **Wuhai** responds best to Scenario 3, indicating socioeconomic development also requires attention.

## 3 Discussion

Comparing with existing research, Du et al. (2022) evaluated water resources-socioeconomic-ecological environment coupling coordination development in northern China, finding socioeconomic subsystem development grew fastest while water resources subsystem lagged behind. This study similarly reveals that during 1998-2022, socioeconomic subsystem indices in the Inner Mongolia Yellow River Basin section ranged 0.47~0.87 with clear upward trends, while water resources subsystem indices fluctuated between 0.47~0.57. Despite different indicator systems, results are fundamentally consistent for the same region and period.

Jiang et al. (2018) found the water resources subsystem lagged behind socioeconomic and ecological environment subsystems in the Inner Mongolia Yellow River Basin section, matching this study’ s conclusion that development speeds rank as: socioeconomic > ecological environment > water resources. This indicates water resources constrain socioeconomic development and ecological maintenance in this region.

Existing studies lack unified approaches to indicator system construction. Zhang et al. (2024) built different water resources-ecological environment indicator systems from multiple perspectives. Future research should follow the Yellow River Basin Ecological Protection and High-Quality Development Planning Outline, adhering to principles of ecological priority, green development, water conservation, tailored measures, and coordinated planning to construct more comprehensive and representative indicator systems.

Few studies have conducted scenario simulation predictions for composite systems. Those that did typically predicted coupling coordination degree directly (e.g., Shi et al., 2021 using ARIMA; Li et al., 2024 using LSTM). This study first improves the LSTM model by adding reality-based constraints derived from indicator physical meanings and objective limits, ensuring the model better follows system internal laws and enhances prediction reliability. Second, unlike traditional approaches, this study proposes recalculating coupling coordination degree using predicted indicator values, capturing changes caused by indicator variations and more accurately identifying how regulation scenario differences affect future coordination. This provides decision-makers with a more precise simulation tool for optimizing resource allocation and policy adjustments to enhance regional development coordination and sustainability.

## 4 Conclusions

The synergistic evolution of water resources, socioeconomic development, and ecological environment is crucial for regional sustainable development. This study employs subsystem evaluation indices, comprehensive evaluation index $T$, and coupling coordination degree $D$ to evaluate spatiotemporal variation characteristics of the water resources-socioeconomic-ecological environment composite system in the Inner Mongolia Yellow River Basin section. The LSTM model was improved to enhance accuracy and prediction practicality, forecasting future coupling coordination development under four regulation scenarios. Main conclusions are:

1) A water resources-socioeconomic-ecological environment composite system evaluation indicator system was constructed. Subsystem evaluation indices were calculated for seven league/cities in the Inner Mongolia Yellow River Basin section. During 1998–2022, development speeds ranked as: socioeconomic subsystem > ecological environment subsystem > water resources subsystem.

2) Using the coupling coordination degree model, composite system comprehensive evaluation index $T$ and coupling coordination degree $D$ were calculated. Both indices ($T$ and $D$) increased year by year across league/cities, with $T$ ranging 0.42~0.58 and $D$ ranging 0.67~0.80. Development speeds varied significantly among cities, with the Hohhot-Baotou-Ordos region as the high-speed development center gradually decreasing outward.

3) Based on four regulation scenario predictions, comparative analysis reveals: **Alxa, Bayannur, and Ulanqab** require joint water resources-socioeconomic regulation; **Wuhai** is best suited for joint socioeconomic-ecological environment regulation; and **Baotou, Hohhot, and Ordos** benefit most from joint water resources-ecological environment regulation.

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