

RESEARCH ON WATER AND LAND RESOURCES REGULATION TECHNOLOGY AND DEVELOPMENT STRATEGIES IN IRRIGATED AREAS OF THE YELLOW RIVER BASIN

RECHERCHE SUR LA TECHNOLOGIE DE RÉGULATION DES RESSOURCES EN EAU ET EN TERRE ET STRATÉGIES DE DÉVELOPPEMENT DANS LES ZONES IRRIGUÉES DU BASSIN VERSANT DE JAUNE

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ABSTRACT

The irrigated areas in the Yellow River Basin are facing severe water scarcity and ecological pressure. The complex interactive feedback relationships among the water-ecology-energy-food (WEEF) nexus constrain regional sustainable development. This study systematically analyzes the WEEF interactive mechanism, establishes a comprehensive evaluation index system, and integrates the XGBoost model with the SHAP method to identify key driving factors. A system dynamics model is employed to simulate the evolution trends of multiple systems. Furthermore, an ecology-oriented collaborative regulation technology and development strategies for water and land resources in irrigated areas are proposed. The research reveals core issues in the Yellow River Basin's irrigated areas, such as water resource overexploitation and imbalanced water-use structure, and quantifies the driving mechanisms of natural and anthropogenic activities on ecosystems and agricultural patterns. The findings provide a scientific decision-making basis for implementing the "Four Water Determinations" principle and for ensuring food security and ecological security in the Yellow River Basin.

Keywords: Yellow River Basin; Irrigated area; Water and land resources; Water-ecology-energy-food (WEEF) coupling; System dynamics; Regulation strategy.

RESUME

Les zones irriguées du bassin versant de Jaune sont confrontées à une grave pénurie d'eau et à des pressions écologiques. Les relations de réaction interactives complexes au sein du lien entre eau-écologie-énergie-alimentation (WEEF) limitent le développement durable régional. Cette étude analyse de manière systématique le mécanisme interactif du lien entre WEEF, établit un système d'indice

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d'évaluation complet et intègre le modèle XGBoost à la méthode SHAP pour identifier les facteurs déterminants clés. Un modèle de dynamique des systèmes est utilisé pour simuler les tendances d'évolution de plusieurs systèmes. En outre, une technologie de régulation collaborative axée sur l'écologie et des stratégies de développement des ressources en eau et en terres dans les zones irriguées sont proposées. La recherche met en lumière des problèmes fondamentaux qui existent dans les zones irriguées du bassin versant de Jaune, tels que la surexploitation des ressources en eau et le déséquilibre de la structure de consommation de l'eau, et quantifie l'impact exercé par des principaux mécanismes des activités naturelles et anthropiques sur les écosystèmes et les modèles agricoles. Les résultats fournissent une base scientifique pour la prise de décision relative à la mise en œuvre du principe des « quatre déterminations de l'eau » et pour assurer la sécurité alimentaire et la sécurité écologique dans le bassin versant de Jaune.

Mots-clés : Bassin versant de Jaune; Zone irriguée; Ressources en eau et en terres; Lien entre eau-écologie-énergie-aliment (WEEF); Dynamique des systèmes; Stratégie de régulation.

INTRODUCTION

The Yellow River Basin is a key ecological security barrier and economic core in China, holding a pivotal strategic position (Han et al., 2026). It faces water scarcity, fragile ecosystems, and food pressure (Li et al., 2025). The water-ecology-energy-food (WEEF) nexus is a highly coupled system where water supports energy and irrigation, while energy consumption affects water and ecology (Sun et al., 2026). Water-land conflicts are acute. Per capita water availability is only 27% of the national average; annual total water supply is 38.8 billion m³, with agricultural use at 69.8% and ecological use at only 3.9% (Gu et al., 2025). Among 69 prefectures, 45.7% are water-overloaded (Guo et al., 2022). Irrigated cropland expanded by 13.4% over the past decade, but irrigation efficiency remains only 0.55, intensifying the water-use conflict (Zhou et al., 2026).

Existing studies focus on single systems, lacking a systematic understanding of WEEF interactions, and thus cannot support the “Four Water Determinations” principle. To address this, this study focuses on typical irrigated areas in the basin. It: (1) analyzes WEEF feedback mechanisms; (2) builds an evaluation index system with correlation diagnosis; (3) uses XGBoost and SHAP to identify key drivers; (4) develops a system dynamics model to simulate future trends; and (5) proposes an ecology-oriented collaborative regulation strategy for water and land resources.

2. METHODOLOGY

2.1 Analysis of the Interactive Feedback Mechanism of the WEEF Nexus

The water-ecology-energy-food (WEEF) system is a multi-element coupled complex giant system with water resources as its central hub. Its interactive feedback mechanism operates as follows: the water resources subsystem provides rigid support for food production and energy development (e.g., hydropower, coal chemical industry) through irrigation and water supply; in contrast, agricultural non-point source pollution and water pollution generated during energy production adversely affect water environment quality and ecosystem health (Tan et al., 2025).

The ecosystem supports the energy and food systems by providing services such as biomass and water conservation, but overexploitation can lead to habitat degradation and functional loss. The socioeconomic subsystem drives the development of each system through policy interventions and technological inputs, while also intensifying competition for water use. Based on this interactive feedback relationship, this study constructs causal feedback loops, thereby laying a theoretical foundation for subsequent system dynamics simulations.

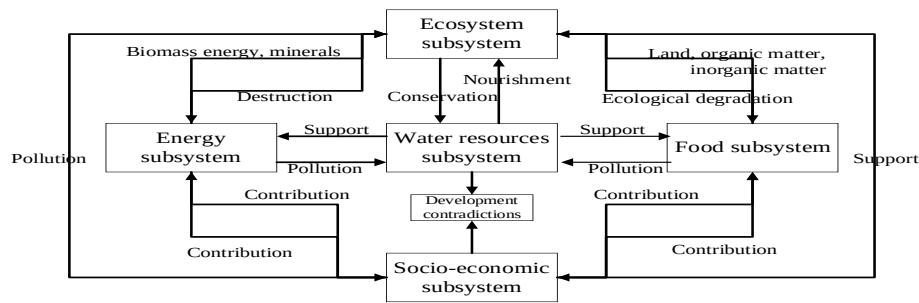


Figure 1. Schematic diagram of the water-ecology-energy-food (WEEF) nexus mechanism

2.2 Analysis of the Current Status of the WEEF Nexus

To systematically analyze the current development status of the water-ecology-energy-food (WEEF) nexus in the Yellow River Basin, this study constructs a multi-dimensional indicator system covering water resources, ecology, energy, food, and social resilience, based on the principles of scientific rigor, systematicity, and data availability. Using relevant statistical data of the Yellow River Basin from 2000 to 2023, a comprehensive evaluation framework is established from three perspectives: reliability, synergy, and resilience. Standardization methods are applied to eliminate dimensional differences among indicators (Niu et al., 2026).

Table 1. Evaluation indicator system for the water-ecology-energy-food (WEEF) complex system in the Yellow River Basin

Principles	Indicator Layer Per capita water resources	Indicator code	Indicator properties
Reliability	Per capita water consumption	X ₁	Positive
	Water yield per unit of land	X ₂	Negative
	Water consumption per 10,000 yuan of GDP	X ₃	Positive
	Yield per unit area	X ₄	Negative
	Per capita grain production	X ₅	Positive
	Energy consumption elasticity coefficient	X ₆	Positive
	Per capita energy consumption (standard coal)	X ₇	Negative
	Vegetation cover	X ₈	Negative
	Proportion of water bodies	X ₉	Positive
	Industrial sulphur dioxide emissions	X ₁₀	Positive
	Total power of agricultural machinery	X ₁₁	Negative
Coordination	Use of chemical fertilisers and pesticides	X ₁₄	Positive
	Water consumption per mu	X ₁₅	Negative
	Proportion of water used in agriculture	X ₁₆	Negative
	Agricultural carbon emissions	X ₁₇	Negative
	Proportion of water used for ecological and environmental purposes	X ₁₈	Negative
	Proportion of water used in industry	X ₁₉	Positive
	Population density	X ₂₀	Negative
Resilience	Urbanisation rate	X ₂₁	Negative
	Proportion of fiscal expenditure allocated to energy conservation and environmental protection	X ₂₂	Positive
	Number of green utility model patents	X ₂₃	Positive
	Indicator Layer	X ₂₄	Positive

To reveal the interactive feedback relationships among indicators of the water-ecology-energy-food (WEEF) complex system and to avoid interference from multicollinearity, a combined Pearson-Spearman correlation analysis was employed. First, Z-score standardization was applied to the raw data. Second, the Pearson correlation coefficient between indicators was calculated as:

$$r_{ij} = \frac{\sum_{k=1}^n (x_{ki} - \bar{x}_i)(x_{kj} - \bar{x}_j)}{\sqrt{\sum_{k=1}^n (x_{ki} - \bar{x}_i)^2} \sqrt{\sum_{k=1}^n (x_{kj} - \bar{x}_j)^2}} \quad (1)$$

And was supplemented by the Spearman rank correlation coefficient for nonlinear verification. Key correlation pairs were identified through significance testing ($\alpha=0.05$). Subsequently, multicollinearity was diagnosed using the variance inflation factor (VIF), calculated as $VIF=1/(1-R^2)$, and redundant indicators with $VIF > 10$ were removed. Through the above steps, core correlation pathways—such as water–energy, water–food, and energy–carbon—were identified, providing a filtered set of independent indicators for the subsequent measurement of coupling coordination degree.

2.3 Analysis of Driving Factors

XGBoost (Extreme Gradient Boosting) is an optimized algorithm based on the traditional Gradient Boosting Decision Tree (GBDT). It incorporates L1/L2 regularization and tree pruning mechanisms to prevent overfitting, while supporting parallel computing to accelerate training efficiency. XGBoost can be widely applied to classification, regression tasks, and feature importance ranking (Fu et al., 2026).

$$\hat{y}_i^{(t)} = \sum_{k=1}^t f_k(x_i) = \hat{y}_i^{(t-1)} + f_t(x_i), f_k \in F \quad (2)$$

where: $\hat{y}_i^{(t)}$ is the predicted result of sample i after the t iteration of the model; $\hat{y}_i^{(t-1)}$ is the predicted result of the previous $t-1$ weak decision trees; $f_t(x_i)$ represents the model of the t tree; F is the set of all possible decision trees.

SHAP (SHapley Additive exPlanations) is a game theory-based method for interpreting the predictions of machine learning models. This method is grounded in the Shapley value (Liu et al., 2026). A SHAP value greater than 0 or less than 0 indicates a positive or negative impact of the feature on the prediction outcome, respectively, while its absolute value reflects the magnitude of the feature's influence on the overall prediction [33-34]. The XGBoost model and its training data are passed to a SHAP explainer, and then the SHAP value for each feature variable is calculated as follows:

$$y_i = y_{\text{base}} + f(x_{i1}) + f(x_{i2}) + \dots + f(x_{ij}) \quad (3)$$

where: y_{base} is the mean value of the target variable across all samples; $f(x_{ij})$ is the SHAP value of x_{ij} .

3. RESULTS

3.1 Current Status of the Study Area

The total amount of water resources in the Yellow River Basin is relatively low and unevenly distributed in both time and space, resulting in a prominent contradiction between water supply and demand. From 2003 to 2024, the average annual total water supply in the Yellow River Basin was approximately 38.8 billion m^3 , of which surface water sources accounted for 65.7%, groundwater sources accounted for 31.7%, and other sources accounted for 2.6%.

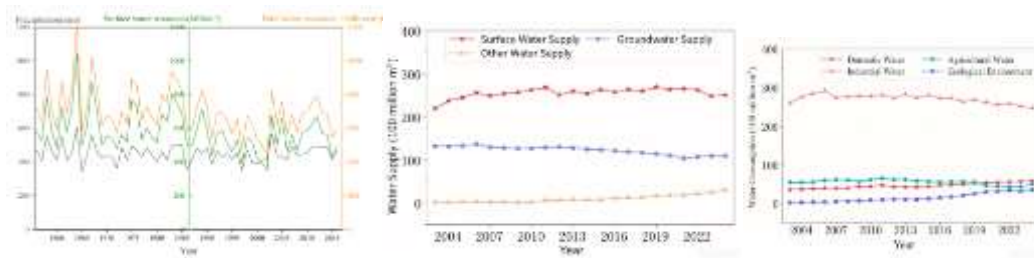


Figure 2. Precipitation, water resources, water supply and consumption in the Yellow River Basin

The Yellow River Basin is an important commercial grain production base in China, with approximately 14.87 million hectares of cultivated land (equivalent to 223 million mu), accounting for 11.2% of the national total cultivated land area. Cultivated land in the basin is mainly distributed along the mainstream and major tributaries of the Yellow River, forming concentrated and contiguous agricultural areas such as the Hetao Plain, the Ningxia Plain, the Fen-Wei Plain, and the Henan-Shandong Plain. Among these, the Henan-Shandong Plain in the lower reaches has the largest cultivated land area, while the Fen-Wei Plain in the middle reaches and the Ningxia-Inner Mongolia irrigated area in the upper reaches are typical irrigated agricultural zones. From the perspective of spatial distribution characteristics, the layout of cultivated land is highly coupled with water resource conditions.

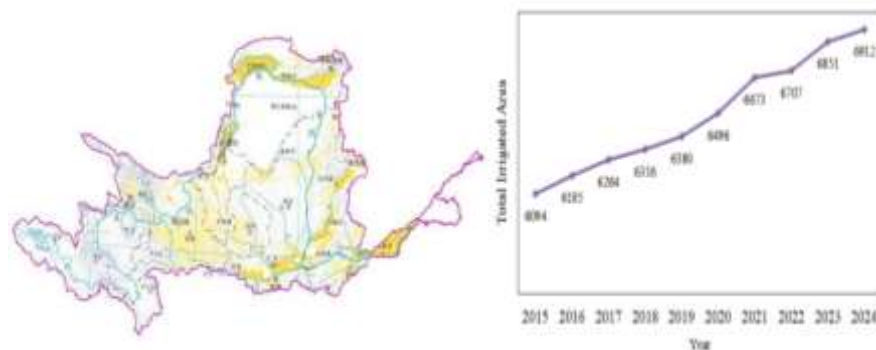


Figure 3. Distribution of cultivated land area and growth trend of irrigated area over the past decade in the Yellow River Basin (current status)

3.2 Analysis of Driving Factors of the Current Status

From 2000 to 2020, water yield, habitat quality, and the proportion of cultivated land area in the Yellow River Basin all exhibited significant spatiotemporal differentiation. The spatial pattern of water yield showed a distribution characterized by low values in the northwest and high values in the southwest and southeast. Temporally, water yield showed a significant increasing trend, rising from 66.7 mm in 2000 to 87.9 mm in 2010, and further to 115.1 mm in 2020.

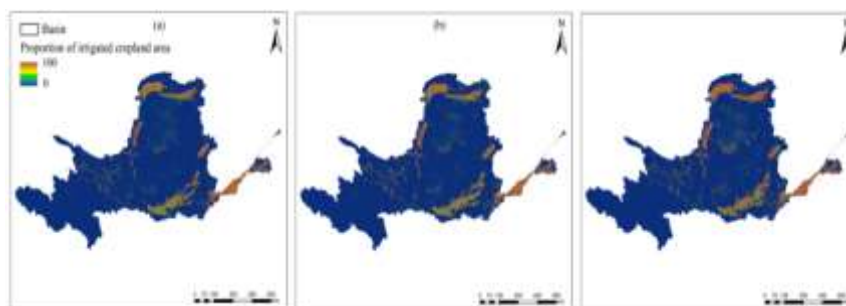


Figure 4. Proportion of irrigated cultivated land area in the Yellow River Basin in 2000 (a), 2010 (b), and 2020 (c)

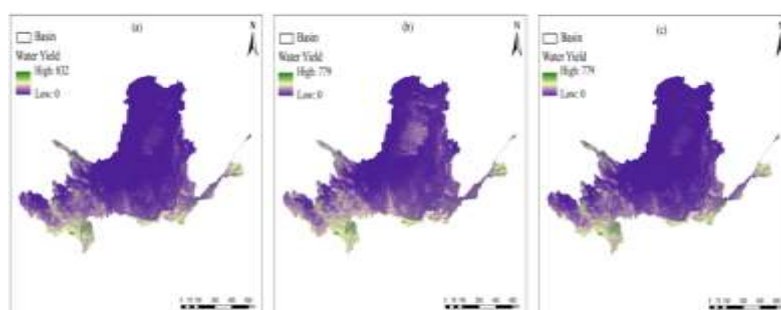


Figure 5. Water yield in the Yellow River Basin in 2000 (a), 2010 (b), and 2020 (c)

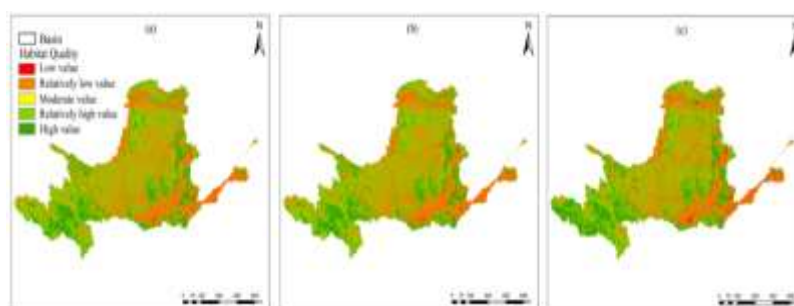


Figure 6. Habitat quality in the Yellow River Basin in 2000 (a), 2010 (b), and 2020 (c)

The XGBoost model was employed to simulate water yield, habitat quality, and the proportion of irrigated cultivated land area. The coefficients of determination (R^2) for the training and test sets of each indicator are shown in the table. For water yield, the R^2 values for the training and test sets ranged from 0.783–0.788 and 0.691–0.730, respectively. For habitat quality, the R^2 values for the training and test sets ranged from 0.763–0.784 and 0.421–0.470, respectively.

Based on the driving factor importance ranking results, significant differences exist in the dominant driving factors and their temporal evolution characteristics for water yield, habitat quality, and the proportion of irrigated cultivated land area in the basin. Water yield is primarily driven by meteorological factors such as precipitation, temperature, and evapotranspiration, and this driving structure remained stable over the study period. For habitat quality, the dominant driving factors include evapotranspiration, population density, NDVI, and DEM. The temporal evolution shows that in 2000, the importance of evapotranspiration was higher than that of population density, whereas in 2010 and 2020, population density surpassed evapotranspiration in importance, indicating an increasing stress effect of human activities on habitat quality.

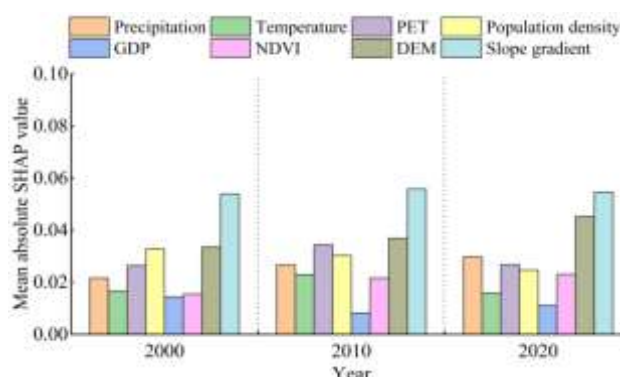


Figure 7. Mean absolute SHAP values of driving factors for habitat quality in the Yellow River Basin

3.3 Ecology-Oriented Regulation Strategies for Water and Land Resources in Irrigated Areas

Strategy 1: Adhere to the “Four Water Determinations” principle and strengthen the rigid constraint of water resources. For water-resource overloaded irrigated areas, formulate and implement water reduction plans within a specified timeframe, and gradually phase out high water-consumption, low-benefit irrigation methods through water right buybacks and fallow subsidies. **Strategy 2:** Accelerate the promotion of deep agricultural water-saving and the modernization of irrigated areas. Simultaneously, promote the construction of high-standard farmland, expand the planting proportion of low water-consumption and high drought-tolerant crops, and select and promote new drought-tolerant crop varieties. **Strategy 3:** Deepen the comprehensive reform of agricultural water pricing, using price leverage to promote water conservation. Establish a pricing mechanism that covers costs and reasonably reflects the scarcity of water resources. **Strategy 4:** Optimize the water source structure and secure the ecological security bottom line. Actively advance the preliminary work of inter-basin water transfer projects such as the West Route and the Second Phase of the East Route of the South-to-North Water Transfer Project, to increase the total water resource carrying capacity of the Yellow River Basin, relieve the squeezed agricultural water use, and effectively replace ecological water use.

CONCLUSION

(1) The current status diagnosis shows that the Yellow River Basin faces a severe water resource overloading problem, with agricultural water use accounting for as high as 69.8% and 45% of prefecture-level administrative regions being in an overloaded state. The irrigated cultivated land area expanded by 13.4% over the past decade, while the effective utilization coefficient of irrigation water remains only 0.573. The cropping pattern of “wheat-dominant, maize-supplemented, and soybean-weak” is subject to the rigid constraint of water resource allocation. (2) The driving mechanism analysis reveals that water yield is overwhelmingly dominated by climatic factors. Habitat quality is increasingly stressed by human activities, with the importance of population density having surpassed that of evapotranspiration. The expansion of irrigated cultivated land is shifting from “population-driven” to “water resource constraint-driven”. (3) The regulation strategies emphasize the “Four Water Determinations” principle as the core, delineating ecological reduction zones, total control zones, and water-saving and efficiency-enhancing zones to implement tiered management.

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