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ORIGINAL RESEARCH ARTICLE

Comprehensive evaluation and application of synergistic pollution management strategies in the Yellow River Basin

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Abstract: Synergistic governance is essential for addressing transregional environmental pollution challenges in the Yellow River Basin. To explore the effect of synergistic environmental pollution management in the Yellow River Basin, we constructed a four-tier index system—driving force, pressure, synergy, and effectiveness—using 2012–2020 panel data from nine provinces. A comprehensive evaluation was performed using an ecological niche suitability model, and a spatial panel econometric model was applied to identify regional spillover effects of pollution diffusion and synergistic management efforts. From 2012 to 2020, the overall effectiveness of coordinated governance in the Yellow River Basin improved from Level V to Level II. The evolution of governance levels across provinces exhibited noticeable spatial heterogeneity, with upstream areas generally exhibiting higher effectiveness than the middle and lower reaches. Spatial model results revealed a significant spatial spillover effect of cross-provincial pollution control, as indicated by the spatial Durbin model, which showed a significant spatial lag term ($p<0.05$). This suggests that pollution control inputs in one province enhanced its own governance efficiency and had a positive impact on neighboring provinces. In addition, robustness checks using the Bootstrap method supported the stability of the ecological niche suitability estimates. Multicollinearity diagnostics indicated no serious collinearity (all variance inflation factor values <5), and the key regression coefficients were statistically significant ($p<0.01$). This study proposes differentiated policy recommendations to enhance coordinated pollution management in the Yellow River Basin, including strengthening cross-regional collaboration mechanisms, establishing unified joint prevention and control assessment indices, increasing environmental inputs and technical support for weaker middle and lower basin regions, and improving ecological compensation and benefit-sharing systems to promote high-quality, sustainable basin development.

Keywords: Yellow River Basin; Synergistic pollution management; Ecological niche suitability; Spatial spillover effect; Policy recommendations

1. Introduction

With the progression of globalization and the acceleration of industrialization, transregional environmental pollution management has become an important global issue. The United Nations' Sustainable Development Goals explicitly call for the strengthening of transboundary water resources and environmental governance, and international frameworks, such as the European Union Water Framework Directive, emphasize synergistic control in transboundary river basins. In recent years, scholars have highlighted that pollution governance is characterized by significant spatial spillovers; sewage discharge and local governance policies can affect the environmental quality of neighboring regions, highlighting the need for a transregional synergistic governance model. In this context, surface aquatic ecosystems in large river basins, such as the Yellow River, are particularly sensitive to anthropogenic pressures, and their management increasingly relies on models that can trace policy impacts across different periods of economic development and governance reform.[1-5]

The Yellow River Basin, as an important region for ecological protection and high-quality development, spans nine provinces in the north of China, namely Shanxi, Shaanxi, Inner Mongolia, Ningxia, Gansu, Qinghai, Henan, Shandong, and Hebei, and geographically ranges from the Tibetan Plateau in the upper reaches of the Yellow River to the North China Plain in the lower reaches of the river, encompassing complex ecosystems and diverse natural environments. There are significant differences in the level of economic development within the basin, and the rapid industrialization and urbanization processes in some areas have further exacerbated environmental pollution pressure.[6] In addition, there are significant differences in policies, technologies, and funds for environmental management among different provinces, making environmental management more challenging. In particular, water, air, and soil pollution in the Yellow River Basin have reached severe levels. The depletion of water resources and deterioration of water quality in the upstream areas have significantly impacted the security of water supply in the middle and lower reaches of the river. Air pollution is mainly concentrated in rapidly industrializing and urbanizing areas, and the transregional transport of atmospheric pollutants has formed a cross-provincial air pollution "transmission belt."[7] Soil pollution risks accumulate in regions with intensive agricultural production and heavy industrial activities, further aggravating soil quality degradation and ecological risks while threatening public health in the Yellow River Basin. In particular, the strong cross-regional mobility of pollutants indicates that environmental pollution control in the Yellow River Basin cannot be effectively addressed by a single region[8] but requires multiregional and cross-provincial synergistic control.[9] Recent global studies have further highlighted that local water pollution and degradation of water quality can generate substantial economic risks through their impact on agricultural productivity and global value chains.[10] Furthermore, socio-economic structures and sector-specific development patterns shape the sustainability of water use and the resilience of water resources.[11] Building on these insights, this study explicitly links the evolution of industrial and agricultural development in the Yellow River Basin to changes in water, air, and soil pollution pressures, thereby situating the basin-level analysis within the broader global debate on the water–economy–environment nexus. To visually connect basin geography with economic activity, Figure 1 depicts the spatial extent of the Yellow River Basin and distinguishes provinces by their relative levels of industrial and agricultural development during the study.

Against this background, the study addresses three interrelated research questions:

(i) How can a quantifiable and multidimensional evaluation index system for cross-regional synergistic environmental pollution management be constructed for the Yellow River Basin, integrating governance drivers, pressures, synergies, and effectiveness?
(ii) Does the synergistic management of environmental pollution in the Yellow River Basin exhibit significant spatial spillover effects, and how can these effects be quantified through an ecological niche suitability framework combined with spatial panel models?
(iii) Which factors play a key role in shaping the performance of synergistic management, and how do upstream and middle-lower reaches differ in their suitability levels?

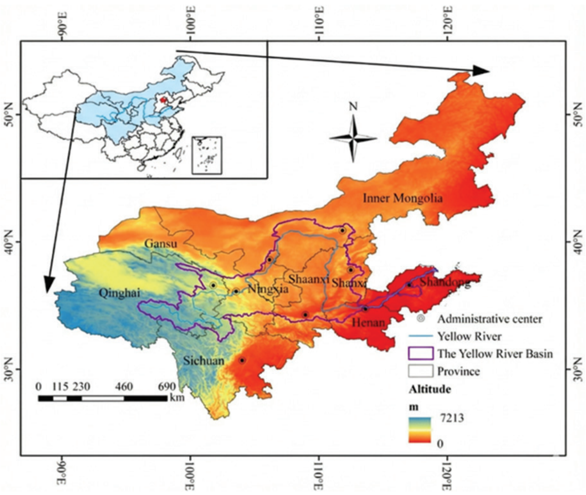

Figure 1. Map of the Yellow River basin. The nine provinces are shaded in three color tones, indicating high, medium, and low combined industrial-agricultural development (based on per-capita industrial value added and agricultural output from 2012 to 2020).

The subsequent sections present the development of the indicator system (Section 3.1), the construction and estimation of the ecological niche and spatial econometric models (Sections 3.2–3.5), and the results and policy implications (Sections 4 and 5) to address these questions.

2. Literature review

2.1. Study on synergistic governance mechanisms across regions

As a key issue in global sustainable development, transregional environmental pollution management has recently attracted extensive attention in the academic community. Internationally, Organisation for Economic Co-operation and Development countries emphasize multi-center synergistic management and horizontal responsibility-sharing mechanisms in watershed management, such as the European Union Water Framework Directive, which promotes the principle of "watershed as a unit and coordination among countries" and provides an important reference for China. Domestic research focuses on institutional design, cooperation frameworks, and the construction of synergistic mechanisms. Zhang *et al*. highlighted that cross-regional pollution management must be based on joint prevention and control mechanisms, as well as the establishment of a system for information sharing, consistency in environmental standards, and joint enforcement.[12] Taking the Yellow River Basin as an example, Lan Nan found that challenges remain in terms of policy fragmentation, unclear division of responsibilities, and insufficient financial support in the current governance.[13] Similarly, Sun and Yu analyzed the foundation logic and implementation path of infrastructure synergistic development in the basin.[14] Most existing studies focus on the normative discussion of macro-policy design and mechanism operation, rather than the quantitative assessment of governance performance and empirical analysis of the effectiveness of synergistic management, leaving a clear methodological gap.

In this study, coordinated (synergistic) governance of environmental pollution in the Yellow River Basin refers to a multi-level and multi-actor governance arrangement in which the central government, basin-level authorities, and provincial and municipal governments jointly formulate and implement policies, share monitoring information, and align regulatory instruments to control water, air, and soil pollution. It emphasizes cross-border collaboration along the river, joint prevention and control of pollutants with strong spatial spillover, and the use of unified standards combined with differentiated local measures. Under this framework, provinces are not treated as isolated units, but as nodes in a coupled socio-ecological system, where governance inputs and outcomes in one province affect neighboring provinces through hydrological and atmospheric linkages.

2.2. Research on pollution control performance evaluation methods

With the increasing severity of environmental problems, traditional governance methods have gradually revealed their inadequacies, making it difficult to cope with the challenges of cross-regional pollution by relying solely on local government environmental protection actions. Therefore, environmental governance in the Yellow River Basin urgently requires the establishment and improvement of synergistic management mechanisms from a broader perspective.[14] This not only requires governments to reach a consensus on policies but also to coordinate the interests of different regions in terms of economic development, industrial structure, and resource allocation.[15-17] In particular, the Yellow River Basin encompasses several provinces with large areas and diverse environmental conditions; therefore, achieving a balance of interests between regions and coordinating the relationship between different development stages and environmental protection needs has become a core issue in synergistic management.[18,19] In this context, scientifically assessing the effectiveness of synergistic governance across different regions has become an important issue in current environmental governance research.[20] The key to assessing the effectiveness of synergistic management lies in the ability to comprehensively consider the results of environmental governance in each region,[21] and to reflect its overall effectiveness through a scientific indicator system.[22]

For the evaluation of synergistic governance, both qualitative and quantitative approaches are employed. Among these, coupled coordination degree models, system dynamics, and genetic algorithms are commonly applied domestically and internationally to measure the synergistic development of watersheds or urban agglomerations. Existing evaluation methods mostly focus on a single pollutant indicator or the governance effect of a single region,[23,24] and therefore lack a comprehensive reflection of inter-regional synergies. Therefore, comprehensively measuring the effect of cross-regional synergistic governance in the Yellow

River Basin through a more systematic and scientific evaluation model has become an urgent need. In the field of ecology and the environment, the ecological niche suitability model has been used to assess land-use suitability and ecosystem services. Hu and Xia,[25] for example, used the ecological niche model for forest land-use suitability assessment to measure sustainability by matching the actual resource ecological niche with the demand ecological niche. The core of this approach is to construct a multidimensional index system of resource ecological niche and match resource allocation with demand for use, thereby assessing the carrying capacity of the environmental system. Based on this idea, incorporating multidimensional pollution management indicators into the ecological niche model of the Yellow River Basin will help reveal the differences in the suitability of coordinated management among regions. For the spatial impacts of pollution management, several studies have applied spatial econometric models. Zhang found that the spatial spillover effects of air pollution indicators accounted for a significant portion of the total impacts using the spatial Durbin model (SDM),[26] highlighting the importance of spatial characteristics in environmental policy formulation. Domestic studies have also gradually focused on spatial correlation. Gu and Gao, based on the SDM, showed that environmental regulation among different regions has imitative or competitive relationships, with significant spatial spillover effects.[24]

Synthesizing the existing literature, it becomes apparent that combining the evaluation of ecological niche suitability with spatial econometric analysis can provide a more comprehensive characterization of the spatial and temporal evolution of watershed pollution synergistic management. In this context, this study reconstructs the indicator system and develops an improved model for the nine provinces and regions in the Yellow River Basin, aiming to provide a more scientific evaluation and policy guidance.

3. Materials and methods

3.1. Construction of the assessment indicator system and data sources

To comprehensively assess the effectiveness of synergistic management of environmental pollution in the Yellow River Basin, this study constructed a multidimensional and hierarchical assessment indicator system, which covers four core aspects: governance driving force, pressure, synergy, and effectiveness. A comprehensive assessment of these indicators can accurately quantify the environmental governance effects in different regions and reveal the problems and challenges in the process of coordinated governance. The four-dimensional structure of drivers, pressures, synergies, and effectiveness was adapted from existing frameworks in transboundary environmental governance and ecological niche-based evaluation of ecosystem management, as summarized in Section 2.2 and detailed in Table 1. In particular, the socio-economic and institutional drivers (X_1) draw on studies of basin-scale governance capacity and green transformation, while the pressure (X_2), synergy (X_3), and effectiveness (X_4) dimensions are informed by previous evaluations of coordinated pollution control and ecological security in large river basins. As shown in Table 1, each indicator is anchored in earlier theoretical and empirical work, including studies on basin governance mechanisms, ecological niche evaluation, and spatial spillover effects. The indicator set, therefore, represents a coherent adaptation of existing frameworks rather than an ad hoc selection of variables.

The governance driving force indicator primarily encompasses the strength of policy support, local government environmental protection investments, and supportive policies for industrial restructuring. It reflects the resources and support that each region can utilize in the process of environmental governance. Specific indicators include per capita disposable income, urbanization level, and the rate of compliance with coordinated environmental pollution management.

The indicator of governance pressure is mainly derived from environmental pollution pressure indicators, including a composite water pollution index (constructed from ammonia nitrogen, chemical oxygen demand, total phosphorus, and selected herbicide concentrations), an air pollution index (based on $PM_{2.5}$, sulfur dioxide, and nitrogen oxides), and a soil pollution index (reflecting heavy metal contents such as cadmium and lead, together with other persistent pollutants).

The governance synergy indicator refers to the level of cooperation and coordination among different provinces and regions in the process of environmental governance, primarily reflected in cross-regional pollutant governance, environmental protection information sharing, and policy synergy. Specific indicators include the degree of synergy in environmental pollution governance policies, in environmental pollution governance actions, and in environmental pollution governance time.

Governance effectiveness indicators are used to assess the actual effectiveness of environmental

Table 1. Indicator system for evaluating the effect of synergistic management of environmental pollution in the Yellow River Basin

Standardized layer	Indicator symbols	Action level	Unit	Properties	Rationale and theoretical anchors	Key references
Drivers of synergistic environmental pollution management (X_1)	X_{11}	GDP per capita	10,000 CNY per person	+	Socio-economic capacity and institutional conditions enable environmental investment and coordinated development in basin governance frameworks	6,7,10,15,18
	X_{12}	Per capita disposable income	Million dollars per person	+		
	X_{13}	Urbanization level (of a city)	%	+		
	X_{14}	Employment rate of the urban population	%	+		
	X_{15}	Environmental pollution synergistic management compliance rate	%	+		
	X_{16}	Life expectancy per urban resident	Year	+		
Pressure for synergistic management of environmental pollution (X_2)	X_{21}	Water pollution index	%	-	Standard stressors in national standards for air, water, and soil, and documented spatio-temporal pressures in the basin and related energy intensity pathways	14,15,21,24
	X_{22}	Air pollution index	%	-		
	X_{23}	Soil contamination index	%	-		
	X_{24}	Urban motor vehicle emission non-compliance rate	%	-		
	X_{25}	Failure rate in the management of construction projects in the city	%	-		
	X_{26}	Carbon intensity of energy consumption	Tons/million	-		
	X_{27}	Annual average concentration of $PM_{2.5}$	ug/m^3	-		
	X_{28}	Total industrial wastewater discharge	tons	-		
Synergies in environmental pollution management (X_3)	X_{31}	Policy synergies in environmental pollution management	%	+	Cross-jurisdictional collaboration operationalized as alignment, joint action, synchronized implementation, co-financing, and eco-economic coupling in synergistic basin governance and coupling- coordination studies	5,10,11, 19,27
	X_{32}	Synergies in environmental pollution control actions	%	+		
	X_{33}	Synergy in the timing of environmental pollution control measures	%	+		
	X_{34}	Synergies of investment in	%	+		

(Cont'd...)

Table 1. ***(Continued)***

Standardized layer	Indicator symbols	Action level	Unit	Properties	Rationale and theoretical anchors	Key references
		environmental pollution control				
	X_{35}	Synergy of urban ecological and economic systems	%	+		
	X_{36}	Ecological protection investment as a share of GDP	%	+		
Effectiveness of synergistic management of environmental pollution (X_4)	X_{41}	Compliance rate for synergistic management of watersheds	%	+	Realized governance performance and service outcomes in environmental governance performance networks and coordinated pollution-control evaluations	4,16,15,21
	X_{42}	Air synergy compliance rate	%	+		
	X_{43}	Soil synergistic management compliance rate	%	+		
	X_{44}	GDP share of investment in environmental pollution control	%	+		
	X_{45}	Public satisfaction with synergistic environmental governance	%	+		
Weighting method		Entropy AHP combined weighting			Established practice for hierarchical environmental and water-security indices, ensuring transparent, replicable weights	23
Modeling perspective		Niche suitability integration			Recent niche theory applications to regional competitiveness and environmental suitability provide a coherent basis for integrating multidimensional indicators	28

Abbreviations: AHP: Analytic hierarchy process; GDP: Gross domestic product.

governance in various regions, with a primary focus on reducing pollutants, enhancing ecological restoration, and protecting ecological functional areas. Specific indicators include the rate of compliance with the standard for coordinated management of waters, the rate of compliance with the standard for coordinated management of air, and the rate of compliance with the standard for coordinated management of soil.

The raw data for socio-economic indicators (X_1: Gross domestic product [GDP] per capita, disposable income, urbanization level, employment rate, and related variables) were obtained from the China Statistical Yearbook,[29] the China City Statistical Yearbook,[29] and the statistical yearbooks of the nine provinces in the Yellow River Basin.[30] Environmental indicators (X_2–X_4), including water, air, and soil pollution indices,

$PM_{2.5}$ concentrations, industrial wastewater discharge, and compliance rates for environmental standards, were taken from the China Environmental Yearbook,[31] the China Environment Statistical Yearbook,[32] and the official bulletin of each province on the state of the environment.[33] All indicators were compiled as balanced annual panel data for 2012–2020 (Table 2).

To investigate the statistical relationships between economic development and environmental pressures, the study computed Pearson correlation coefficients between representative economic indicators (such as GDP per capita and urbanization level) and environmental stress indicators (such as the water pollution index and $PM_{2.5}$ concentration) across provinces and years. In addition, these variables were incorporated into the spatial panel econometric model presented in Section 3.5, where their joint effects on the composite governance index were estimated.

Data were derived from actual measurements taken by environmental monitoring stations and ecological and environmental authorities.

To aggregate the indicators within each dimension, the study adopted a combined weighting method that integrates objective entropy weights with subjective analytic hierarchy process (AHP) weights. First, the panel data matrix of standardized indicators was constructed, and indicator-specific entropy values and entropy-based weights were calculated to capture the degree of information variation across provinces and years. Second, AHP was applied to pairwise comparisons of the four criterion layers (drivers, pressures, synergies, and effectiveness) and their sub-indicators, based on a panel of experts in environmental governance and basin management. Third, the final weight for each indicator was obtained as a convex combination of the

Table 2. Basic information for the assessment of the effectiveness of synergistic management of environmental pollution in the Yellow River Basin

Indicator	2012	2013	2014	2015	2016	2017	2018	2019	2020
X_{11}	6.84	7.61	8.07	8.78	9.04	9.72	10.06	10.57	11.65
X_{12}	4.68	4.86	5.06	5.53	5.86	6.27	6.86	7.13	7.85
X_{13}	75.24	75.82	76.51	77.73	78.47	79.36	79.46	81.27	82.63
X_{14}	79.13	79.62	81.05	81.72	82.45	83.47	84.51	85.27	86.36
X_{15}	87.62	88.46	89.66	90.79	91.48	92.63	93.47	94.61	95.02
X_{16}	84.81	85.01	85.42	85.82	86.14	86.86	87.63	88.15	88.91
X_{21}	150.37	146.28	135.28	125.37	121.27	116.56	108.64	99.56	96.47
X_{22}	184.52	167.42	154.21	148.52	142.38	139.51	132.58	121.47	108.32
X_{23}	141.27	138.24	132.35	128.42	125.36	121.27	118.52	116.47	112.25
X_{24}	2.1624	2.0647	1.9741	1.8752	1.7213	1.5251	1.4637	1.3225	1.2115
X_{25}	3.3126	3.2651	3.0416	2.9625	2.7525	2.6427	2.5415	2.4517	2.3121
X_{26}	3.2146	3.1427	3.1327	3.0851	3.0217	2.9726	2.9125	2.8327	2.7826
X_{27}	108	102	95	88	80	72	65	58	48
X_{28}	1,200	1,150	1,100	1,050	1,000	950	850	700	600
X_{31}	92.17	92.61	93.25	93.87	94.16	94.63	95.26	96.04	96.87
X_{32}	85.37	86.26	87.62	88.25	89.16	89.67	90.52	91.41	92.37
X_{33}	87.28	88.67	89.14	89.85	90.21	90.74	91.51	92.36	93.27
X_{34}	85.89	86.28	86.85	87.41	87.84	88.21	88.67	89.15	89.89
X_{35}	85.46	85.93	86.26	86.78	87.04	87.36	87.85	88.06	88.94
X_{36}	0.85	1	1.2	1.4	1.6	1.75	2	2.2	2.4
X_{41}	89.31	90.72	92.63	94.17	95.37	96.45	97.52	98.02	98.65
X_{42}	86.56	87.27	88.47	89.15	89.56	89.87	90.21	90.81	91.56
X_{43}	87.26	87.85	88.45	88.92	89.93	90.26	90.81	91.27	92.46
X_{44}	1.72	1.81	1.68	1.62	1.59	1.55	1.48	1.53	1.51
X_{45}	89	90	91	92	92	93	94	95	96

Note: Descriptions of indicators are presented in Table 1.

entropy-based and AHP-based weights, following the practice of integrated weighting in environmental and water-resource assessment studies.[34] This approach balanced data-driven variation with expert knowledge and has been widely applied in recent multi-criteria environmental evaluations.

3.1.1. Entropy method for calculating objective weights

First, based on the panel data of nine provinces from 2012 to 2020, the entropy method was used to calculate the dispersion and information entropy of each criterion-level and indicator-level variables to determine the objective weights.

3.1.2. AHP calibration of subjective weights

To introduce expert judgment to complement the importance of the indicators, seven experts from the field of environmental sciences and regional governance were invited to fill in the pairwise comparison matrix and calculate the consistency ratio (all consistency ratios were <0.1, meeting the standard requirement) to obtain the subjective weights of the indicators.

3.1.3. Combined weighting method

The final weights, *W*, were determined using linear weighting for integration, as shown in Equation (1):

$$W_j = \alpha \cdot W_j^{entropy} + (1-\alpha) \cdot W_j^{AHP} \tag{1}$$

Where α is the weight fusion parameter, which was set to 0.6 in this study, i.e., focusing more on the objective difference weights.

The weights of the four criterion layers of driving force (X_1), pressure (X_2), synergy (X_3), and effectiveness (X_4) were finally determined to be 25.4%, 24.1%, 26.8%, and 23.7%, respectively (calculated by the entropy value method and corrected by experts). This study employed a combined weighting approach integrating the entropy method (60%) and the AHP (40%), using objective entropy-derived weights while incorporating expert-based consistency judgments to ensure a balanced evaluation system that reflects both data-driven rigor and informed experience. This hybrid method adheres to established research practices and exhibits strong adaptability and reliability.[35]

3.2. Conventional ecological niche suitability modeling

Conventional ecological niche suitability modeling is a tool based on ecological niche theory that measures the suitability of an area for organisms to survive under specific environmental conditions. The ecological niche theory is derived from species ecology and centers on the relationship between species and their environment, as well as how species are adapted to their ecological niche. To apply the theory to real-world problems, conventional ecological niche suitability models assess the ecological niche suitability of different regions by quantitatively analyzing environmental factors.

In many river basin applications, environmental quality is summarized through composite indicators, such as the water quality index (WQI), which is often combined with multivariate statistical analyses to disentangle the contributions of different pollutants and sources.[29] Building on this line of work, the present study extends the ecological niche suitability framework to a multidimensional composite index that simultaneously accounts for water, air, and soil pollution indicators, as well as socio-economic and governance factors.

The construction of the conventional ecological niche suitability model is particularly important for assessing the effect of coordinated environmental pollution control in the Yellow River Basin. It can accurately reflect the suitability of each region under environmental pollution control measures by standardizing various indicators of environmental pollution. Therefore, this study first constructed a conventional ecological niche suitability model and, in combination with the actual situation of the Yellow River Basin, developed assessment criteria specifically tailored to the Yellow River Basin through the standardization of various assessment indicators.

In constructing the model, it is necessary to define the ecological factors first. These factors are used to characterize various aspects of environmental quality, including water quality, air quality, and soil contamination, among others. It is assumed that there are *n* ecological factors in a given region, denoted by X_i, thus forming an ecological factor matrix, where the rows of the ecological factor matrix represent different regions, and the columns represent different ecological factors. These quantitative values are standardized to ensure comparability of different indicators. The ecological factor matrix was denoted as: $X_i = \{X_1, X_2, X_n\}$. The matrix of quantitative values of the ecological factor (n × m) dimension of the *m* regions was denoted by *EFM*, and the mathematical expression of the ecological factor matrix is shown in Equation (2):

$$EFM = \begin{pmatrix} x_1(t_1) & x_2(t_2) & \cdots & x_n(t_1) \\ x_1(t_2) & x_2(t_2) & \cdots & x_n(t_2) \\ \vdots & \vdots & \vdots & \vdots \\ x_1(t_m) & x_2(t_m) & \cdots & x_n(t_m) \end{pmatrix} \tag{2}$$

Where i = 1,2, n, j = 1,2, m, and $f(E) = (x_i) = [x_1(t_j), x_2(t_j), x_n(t_j)]$ is a subset of the n-dimensional ecological factor space E^n at the time t_j. The non-negative function $f(E)$ represents the ecological niche of the environmental pollution cooperative management system at the time t_j, and the closeness between the actual value of the ecological factor X_i and the optimal value is expressed by NS_t, where $NS_t = \tau(X_i, X_\alpha)$. The ecological niche suitability model is expressed as follows in Equation (3):

$$NS_t = \sum_{i=1}^{n} \frac{\delta_{\min} + \lambda\delta_{\max}}{\delta_{it} + \lambda\delta_{\max}} = \sum_{i=1}^{n} \frac{\min\left[\left|x_i'(t_j) - x_i'(\alpha)\right|\right] + \max\lambda\left[\left|x_i'(t_j) - x_i'(\alpha)\right|\right]}{\left|x_i'(t_j) - x_i'(\alpha)\right| + \max\lambda\left\{\left|x_i'(t_j) - x_i'(\alpha)\right|\right\}} \tag{3}$$

Here, $\delta_{it} = \left|x_i(t_j) - x_i(\alpha)\right|$;
while $\delta_{\max} = \max\{\delta_{it}\} = \max\left\{\left|x_i(t_j) - x_i(\alpha)\right|\right\}$ and $\delta_{\min} = \min\{\delta_{it}\} = \min\left\{\left|x_i(t_j) - x_i(\alpha)\right|\right\}$, Where i = 1,2, m; t = 1,2, n; and λ is the model coefficient $0 \le \lambda \le 1$, treated here as an average of $\lambda = 0.5$.

The conventional ecological niche suitability model calculates the ecological niche suitability of each region by evaluating the proximity between the ecological factors and the optimum values for that region. The non-negative function was used to represent the ecological niche of the Synergistic environmental pollution management system at a certain point in time. To further enhance the applicability and accuracy of the model, the average value of each ecological factor was used as the weighting coefficient in this study. This was to ensure that different ecological factors were balanced and to avoid the excessive influence of a single factor. Through the reasonable selection of weights, the model can reflect the ecological suitability of different regions in environmental pollution management and provide data support for further policy formulation and management.

3.3. Spatial ecological niche suitability model

The spatial ecological niche suitability model is a further extension of the ecological niche theory, which not only focuses on the suitability of a region under specific environmental conditions at a given moment in time, but also considers the spatial distribution and the spatial heterogeneity of environmental factors. In assessing Synergistic environmental pollution management in the Yellow River Basin, the development of a spatial ecological niche suitability model facilitates a more comprehensive understanding of the performance of different regions in the pollution management process. This model can assess the spatial ecological suitability of different regions, providing a basis for optimizing regional pollution management measures.

The spatial ecological niche suitability model employed in this study followed the general logic of habitat suitability modelling under niche theory, whereby a set of environmental and governance variables is related to a suitability index that reflects the "fitness" of regional governance performance.[36] In our context, the ecological niche was interpreted in socio-ecological terms, capturing how well regional pollution control capacities match the multi-media environmental pressures they face.

In practice, the spatial ecological niche suitability model relies on the normalization of assessment indicators. To facilitate the comparison of environmental conditions in different regions, this study adopted the normalization processing method to rescale all assessment indicators to the range (0,1). The purpose of normalization is to eliminate the influence of differences in the scale of each assessment indicator on the assessment results, allowing each indicator to be compared on a uniform scale. The normalization process used the maximum value of the assessment indicator, which is calculated using the following Equation (4):

$$\begin{cases} X_i'(t_j) = X_i(t_j) \cdot \left[ZXLI_X(t_j)\right]^{-1} & (\textit{forward pointer}) \\ X_i'(t_j) = 1 - X_i(t_j) \cdot \left[NXLV_S(t_j)\right]^{-1} & (\textit{contrary indicator}) \end{cases} \tag{4}$$

Where $ZXLI_X(t_j)$ is the maximum value of the forward assessment indicator, and $NXLVs\ (t_j)$ is the maximum value of the reverse indicator. If $X_i\ (\alpha)$ is the optimal value of the assessment indicator and $X'_{i\alpha}$ is the optimal value after normalization (Equation [5]):

$$\begin{cases} X_i'(\alpha) = X_i(\alpha) \cdot \left[ZXLI_X(t_j)\right]^{-1} & (\textit{forward pointer}) \\ X_i'(\alpha) = 1 - X_i(\alpha) \cdot \left[NXLV_S(t_j)\right]^{-1} & (\textit{contrary indicator}) \end{cases} \tag{5}$$

Based on this, the following subsections derive absolute and relative ecological niche suitability indices, and Section 3.6 integrates them into a comprehensive spatial ecological niche suitability index.

3.4. Absolute ecological niche suitability model

The absolute ecological niche suitability measurement model was constructed according to the ecological niche theory and method. The absolute ecological niche suitability model is a quantitative measure of the ecological niche suitability of each region, calculated by comparing the dimensionless processed assessment indexes with the optimal value. It measures the ecological niche suitability of the region by calculating the Euclidean distance between the actual ecological niche value and the optimal ecological niche value. The higher the proximity between the actual ecological niche and the optimal ecological niche, the better the synergistic management of environmental pollution in the region. Using the standardized indicator values, the absolute-zero transformation model was applied to obtain the absolute-zero-adjusted assessment indicators. Let x'_{it} denote the value of an assessment indicator after absolute zero transformation, $x'_{i\alpha}$ its corresponding optimal value, $X'_{it}(0)$ the ecological niche value after transformation, and $X'_{i\alpha}(0)$ the optimal ecological niche value. The specific transformation formula is given in Equation (6):

$$\begin{cases} X'_{it}(0) = x'_i(t_j) - x'_1(t_j) = \left(x'_{1t}(0), x'_{2t}(0), \cdots, x'_{nt}(0)\right) \\ X'_{i\alpha}(0) = x'_i(t_j) - x'_1(0) = \left(x'_{1\alpha}(0), x'_{2\alpha}(0), \cdots, x'_{n\alpha}(0)\right) \end{cases} \tag{6}$$

Based on the results of the absolute zero conversion calculation, the proximity of the actual ecological niche to the most suitable ecological niche was determined using the distance formula, and the absolute ecological niche suitability ($ANS_{t\alpha}$) was calculated using Equation (7):

$$ANS_{t\alpha} = \frac{1 + |S_\alpha| + |S_t|}{1 + |S_\alpha| + |S_t| + |S_\alpha - S_t|} \tag{7}$$

Where $|S_t| = \left|\sum_{i=2}^{n-1} x'_{it}(0) + 0.5x'_{nt}(0)\right|$;

$|S_\alpha| = \left|\sum_{i=2}^{n-1} x'_{i\alpha}(0) + 0.5x'_{n\alpha}(0)\right|$; and

$|S_\alpha - S_t| = \left|\sum_{i=2}^{n-1}\left[x'_{i\alpha}(0) - x'_{it}(0)\right]\right| + 0.5\left[x'_{m\alpha}(0) - x'_{nt}(0)\right]$.

3.5. Relative ecological niche suitability modeling

The relative ecological niche suitability model is similar to the absolute ecological niche suitability model, but it focuses more on comparisons of relative changes in regions than on closeness between absolute values. This model assesses the environmental suitability of a region over a specific time period by examining the relative changes in an ecological factor across multiple regions or time points. Unlike absolute ecological niche suitability, relative ecological niche suitability reflects trends in relative changes in regional suitability by comparing the ratio of ecological niche changes across regions or over time. It is also necessary to first calculate the relative zero transformation, a method named for the process of subtracting 1 from the ratio, where the first rows obtained are all zeros. If x''_{it} denotes the value of the assessment indicator after relative zero-imaging, $x''_{i\alpha}$ denotes the optimal value of the assessment indicator after relative zero-imaging, $X''_{it}(0)$ denotes the value of the ecological niche after relative zero-imaging, and $X''_{i\alpha}(0)$ denotes the optimal value of the ecological niche after relative zero-imaging. The specific formula for calculating the relative absolute-zero transformation is shown in Equation (8):

$$\begin{cases} X''_{it}(0) = x''_i(t_j) \times \left[x''_1(t_j)\right]^{-1} - 1 \\ \qquad = (x''_{1t}(0), x''_{2t}(0), \cdots, x''_{nt}(0)) \\ X''_{i\alpha}(0) = x''_i(\alpha) \times \left[x''_1(\alpha)\right]^{-1} - 1 \\ \qquad = (x''_{1\alpha}(0), x''_{2\alpha}(0), \cdots, x''_{n\alpha}(0)) \end{cases} \tag{8}$$

Based on the results of the relative zero conversion formula, the proximity of the actual ecological niche to the most suitable ecological niche was determined using the distance formula, and the relative ecological niche suitability ($RNS_{t\alpha}$) was calculated using Equation (9):

$$RNS_{t\alpha} = \frac{1 + |S'_\alpha| + |S'_t|}{1 + |S'_\alpha| + |S'_t| + |S'_\alpha - S'_t|} \tag{9}$$

Where $|S'_t| = \left|\sum_{i=2}^{n-1} x''_{it}(0) + 0.5x''_{nt}(0)\right|$;

$|S'_\alpha| = \left|\sum_{i=2}^{n-1} x''_{i\alpha}(0) + 0.5x''_{n\alpha}(0)\right|$; and

$|S'_\alpha - S'_t| = \left|\sum_{i=2}^{n-1}\left[x''_{i\alpha}(0) - x''_{it}(0)\right]\right| + 0.5\left[x''_{m\alpha}(0) - x''_{nt}(0)\right]$.

The advantage of the relative ecological niche suitability model is that it can reflect the relative changes in ecological factors between regions, and is particularly suitable for environmental conditions with no absolute suitability value or no specific optimal value in a certain time period. This gives the model a clear advantage in dynamic monitoring and long-term trend analysis. In this way, the trend of ecological suitability over time can be better revealed, thus providing predictions and guidance for long-term environmental management and pollution control measures.

In addition to the flexibility in time span, relative ecological niche suitability can also provide a relative comparison of different regions in the treatment process. For example, in different regions of the Yellow River Basin, due to variations in geography, climate, and other environmental conditions, the ecological conditions and the effectiveness of pollution management differ significantly. Through this relative assessment method, it is possible to avoid unreasonable assessment results when a single environmental factor is extremely high or low in a particular region.

3.6. Comprehensive spatial ecological niche suitability index

Building on the absolute ecological niche suitability model (Section 3.4) and the relative ecological niche suitability model (Section 3.5), this subsection constructs a comprehensive spatial ecological niche suitability index. This index reflects the overall ecological suitability of each province by weighting and integrating both absolute and relative suitability components. In this model, the absolute and relative ecological suitability of each region were calculated first. Then, the weights of these two factors in the final assessment were determined based on the results of expert judgment or data analysis. If W denotes the absolute ecological niche suitability weights and $1-W$ is the relative ecological niche suitability weights, the spatial ecological niche suitability model $SNS_{t\alpha}$ can be expressed as Equation (10):

$$SNS_{t\alpha} = W.\ ANS_{t\alpha} + (1-W)\ RNS_{t\alpha} \tag{10}$$

Where $W \in [0,1]$, weights W tend to 0, spatial ecological niche suitability tends to $RNS_{t\alpha}$; weights W tend to 1, spatial ecological niche suitability tends to $ANS_{t\alpha}$; in the equilibrium condition, take $W = 0.5$.

To avoid calculation bias, all index data were processed using the same standardization method, and the absolute suitability and relative suitability were assigned a similar range of values (both 0–1), ensuring comparability. Based on this normalization, equal weights of 0.5 were assigned to each component for synthesis.

3.7. Spatial econometric models

To portray the spatial dependence of governance effectiveness across the basin provinces, this study introduced a spatial econometric analysis. A spatial weight matrix was constructed to capture the spatial linkages induced by geographical or administrative proximity. Based on this, the spatial lag model (SLM) and the SDM were developed. SLM includes the spatial lag term of the dependent variable, as shown in Equation (11).

$$Y = \rho WY + X\beta + \varepsilon \tag{11}$$

Where Y is the ecological niche suitability index, and ρ is the spatial spillover coefficient. SDM further introduces a spatial lag term for the independent variables, as shown in Equation (12).

$$Y = \rho WY + X\beta + WX\theta + \varepsilon \tag{12}$$

To further enhance the rigor of model setting, this study first identified significant spatial autocorrelation in ecological niche suitability (Moran's I test, $p<0.01$), indicating the necessity of employing a spatial econometric model. Based on this, the Lagrange Multiplier (LM) test and the robust LM test were used for model selection. The results showed that both the spatial lag term and the spatial lag term of the explanatory variables were significant, making it suitable to use the SDM. Based on the LM, the Wald test was used to compare the SDM and SLM models, and the results showed that the SDM model was superior to the SLM (Wald test statistic value = 35.44, $p<0.001$), rejecting the hypothesis that the SDM degenerates into the SLM. Therefore, this paper ultimately selected the fixed-effects SDM as the primary regression model, which accounts for year effects and unobservable heterogeneity across provinces to mitigate estimation bias.

The statistics reported in Table 3 were obtained from the maximum-likelihood estimation of candidate spatial models using the panel-data module of SDM, which followed the standard definitions in the spatial econometrics literature.

For the spatial weights matrix, an inverse-distance spatial weights matrix was used, constructed based on the geographic distance between provincial capital cities. The weights matrix was then row-standardized to ensure symmetry and a zero main diagonal. The setup not only conformed to the spatial mechanism of pollution diffusion in the watershed, but also captured the spatial linkage effect of governance behaviors. The form of the setting refers to the approach adopted by Li and Wang in their study on ecological compensation in the Yellow River Basin.[37]

Beyond this baseline specification, the authors acknowledge that distance is not the only channel of interdependence. Consistent with the spatial econometric literature, the specification of weights can influence parameter estimates. Accordingly, as a robustness check, the SDM was re-estimated using a binary contiguity matrix, where 1 indicates that two provinces share a border and 0 indicates that they do not. The signs and statistical significance of key coefficients remain qualitatively similar to those in the baseline inverse distance results (Table 4), indicating that the principal inferences, particularly the positive and significant spatial spillovers, are not an artifact of the distance-based weighting. The detailed estimation results of the SDM are presented in Table 5.

3.8. Robustness tests

The variance inflation factor (VIF) test for the main explanatory variables reveals that the VIF values for all variables are <5, with a maximum VIF of 3.21 and a mean of 2.07. This indicates that there is no serious multicollinearity problem, ensuring the stability of the regression coefficient estimates.

The spatial autocorrelation test of synergistic governance efficacy using Moran's I indicator showed that the Moran's I values for each year from 2012 to 2020 were significantly greater than 0, with a $p<0.01$, indicating a significant positive spatial agglomeration among the regions. The necessity of constructing a spatial regression model was verified.

Repeated sampling (1,000 times) of the ecological niche suitability index using the Bootstrap nonparametric method was used to construct 95% confidence intervals (CIs) for the estimates in each year. The results showed that the trend of governance performance improvement was statistically significant (the intervals did not

Table 3. Model selection diagnostics for spatial panel models

Test	Model comparison/null hypothesis	Statistic	*p*-value	5% decision	Implication
LM (lag)	H_0: No spatial lag dependence (ρ=0)	15.23	0.002	Reject H_0	Spatial lag dependence is present
LM (error)	H_0: No spatial error dependence (λ=0)	12.47	0.005	Reject H_0	Spatial error dependence is present
Robust LM (lag)	H_0: No spatial lag dependence conditional on error	3.45	0.032	Reject H_0	The lag effect remains after controlling for error
Robust LM (error)	H_0: No spatial error dependence conditional on lag	2.89	0.045	Reject H_0	The error effect remains after controlling for lag
Wald χ^2 (2) (SDM→SAR/SLM)	H_0: SDM degenerates to SAR/SLM ($\gamma = 0$ restrictions)	35.44	<0.001	Reject H_0	SDM preferred over SAR/SLM
LR (SDM vs. SAR/SLM)	H_0: SAR/SLM fits as well as SDM	15.78	<0.001	Reject H_0	SDM fits significantly better than SAR/SLM
LR (SDM vs. SEM)	H_0: SEM fits as well as SDM	12.34	0.002	Reject H_0	SDM fits significantly better than SEM

Abbreviations: H0: Null hypothesis; LM: Lagrange Multiplier; LR: Likelihood ratio; SAR: Spatial autoregressive model; SDM: Spatial Durbin model; SEM: Spatial error model; SLM: Spatial lag model.

Table 4. Robustness to alternative spatial weights (*W*)

Variable	Expected sign	Inverse distance *W* sign	Inverse distance *W* significance	Contiguity *W* sign	Contiguity *W* significance	Consistency across *W*
Environmental investment intensity	+	+	$p<0.05$	+	$p<0.05$	Yes
Industrial structure upgrading	+	+	$p<0.05$	+	$p<0.05$	Yes
Industrial pollution intensity	−	−	$p<0.05$	−	$p<0.05$	Yes
Urbanization pressure	−	−	$p<0.05$	−	$p<0.05$	Yes
Economic development linear term	−	−	$p<0.05$	−	$p<0.05$	Yes
Economic development quadratic term	+	+	$p<0.05$	+	$p<0.05$	Yes
Spatial lag term rho	+	+	$p<0.01$	+	$p<0.01$	Yes
Controls for year and province fixed effects	—	Included	—	Included	—	—

Table 5. Detailed regression results of the spatial Durbin model

Variable	Coefficient	Standard error	*t*-statistic	*p*-value
Spatial lag term (ρ)	0.327	0.089	3.67	<0.001
Environmental investment intensity (X_{44})	0.215	0.063	3.41	0.002
Industrial structure upgrading	0.189	0.057	3.31	0.003
Industrial pollution intensity (X_{28})	−0.246	0.071	−3.46	0.002
Urbanization pressure (X_{13})	−0.178	0.062	−2.87	0.006
Economic development (linear term, X_{11})	−0.153	0.059	−2.59	0.013
Economic development (quadratic term, X_{11}^2)	0.098	0.038	2.58	0.014
Year fixed effects	Included	—	—	—
Province fixed effects	Included	—	—	—
R^2	0.786	—	—	—
F-statistic	42.35	—	—	<0.001

overlap across years) and supported the validity of the spatial modeling setup. The model parameters were estimated using maximum likelihood estimation, which was implemented in R (version 4.4.1) using the spdep and splm packages. To ensure robustness, the potential heteroskedasticity and serial correlation were addressed using Driscoll-Kraay robust standard errors, thereby improving the robustness of the regression results.

4. Results and discussion

Based on the ecological niche suitability models and assessment criteria, the results indicate a clear and statistically significant improvement in the coordinated governance effectiveness index of the Yellow River Basin from 2012 to 2020. The composite index rose from lower-level suitability in the early years to substantially higher suitability levels by 2020, and most provinces experienced a steady upward trajectory rather than short-lived fluctuations. At the same time, the spatial pattern exhibited pronounced regional differentiation, with upstream provinces generally achieving higher governance suitability than some middle- and downstream provinces. The spatial econometric results confirm significant spillover effects of governance performance across neighboring provinces. These empirical findings provide the basis for the subsequent detailed discussion of standards, indicator behavior, and policy implications.

4.1. Reference to national and local standards

In formulating the assessment standards, this study referred to China's Surface Water Quality Standards (GB3838–2012), Ambient Air Quality Standards (GB3095–2012), and Soil Environmental Quality Standards (GB36600–2018). Specifically, the surface water indicators adhered to the threshold ranges for Levels I-V water quality outlined in the Environmental Quality Standards for Surface Water (GB3838–2002), and the air quality indicators corresponded to the Grade I–III categories in the Ambient Air Quality Standards (GB3095–2012). Soil indicators were aligned with the risk screening and intervention values specified in the Soil Environmental Quality Standards (GB36600–2018). These national thresholds were mapped to the five ecological niche levels (Level I–V) used in this study, ensuring consistency between the ecological niche levels and official environmental quality categories. These standards provide a unified basis for measuring ecological environment quality, ensuring the uniformity and comparability of each assessment indicator on a national scale. At the same time, the content of the standards was refined and adjusted by combining the local standards and actual conditions in various parts of the Yellow River Basin.

In terms of surface water, air quality, and soil quality, different areas of the Yellow River Basin may be affected by various sources of pollution, presenting distinct challenges and requiring different treatment methods. Therefore, when formulating assessment criteria, national standards served as the primary benchmark, while local characteristics and dominant pollution types were reflected through weighting and the selection of indicators. For example, in provinces where industrial wastewater and agricultural non-point source pollution were prominent, greater weight was assigned to surface water indicators such as ammonia nitrogen, chemical oxygen demand, total phosphorus, and herbicide concentrations. In cities with persistent air quality problems, indicators related to $PM_{2.5}$ and sulfur dioxide reductions received higher weights. In areas with intensive mining or heavy chemical industries, soil indicators focusing on heavy metals (e.g., cadmium, lead) were emphasized. These concrete adjustments, summarized in Table 6, ensured that the national standards were operationalized in a way that reflects the actual pollution pressures and governance priorities in each province.

4.2. Specific elements and indicators of assessment criteria

The panel dataset covered nine provinces over 9 years (2012–2020), allowing the study to capture not only cross-sectional heterogeneity but also temporal dynamics. During this period, the average GDP per capita and urbanization level increased steadily, while key environmental pressure indicators, such as the water pollution index, $PM_{2.5}$ concentrations, and industrial wastewater discharge, showed a declining trend. These evolutions underpin the observed upward trend in the composite governance index.

The specifics of the assessment criteria were based on a number of pollutant indicators determined by analyzing environmental quality monitoring data from various regions of the Yellow River Basin. These indicators included, but were not limited to, water pollutants (e.g., ammonia nitrogen, chemical oxygen demand, total phosphorus, and typical herbicides), air pollutants (e.g., $PM_{2.5}$, sulfur dioxide, nitrogen oxides), and soil pollutants (e.g., heavy metal contents such as

Table 6. Criteria for evaluating the effectiveness of synergistic management of environmental pollution in the Yellow River Basin

Indicator	Level I (excellent)	Level II (good)	Level III (medium)	Level IV (qualified)	Level V (failed)
X_{11}	>15	(10,15)	(7.5,10)	(5,7.5)	<5
X_{12}	>8	(6,8)	(4,6)	(2,4)	<2
X_{13}	>80	(60,80)	(50,60)	(40,50)	<40
X_{14}	>90	(80,90)	(70,80)	(60,70)	<60
X_{15}	>90	(80,90)	(70,80)	(60,70)	<60
X_{16}	>90	(80,90)	(70,80)	(60,70)	<60
X_{21}	(0,70)	(70,150)	(150,200)	(200,300)	>300
X_{22}	(0,70)	(70,150)	(150,200)	(200,300)	>300
X_{23}	(0,70)	(50,150)	(150,200)	(200,300)	>300
X_{24}	<1	(1,2)	(2,3)	(3,4)	>4
X_{25}	<1	(1,3)	(3,5)	(5,7)	>7
X_{26}	<2	(2,3)	(3,4)	(4,5)	>5
X_{27}	≤35	(35,50)	(50,75)	(75,100)	>100
X_{28}	≤200	(200,500)	(500,1,000)	(1,000,2,000)	>2,000
X_{31}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{32}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{33}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{34}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{35}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{36}	≥2.5	(2.0,2.5)	(1.5,2.0)	(1.0,1.5)	<1.0
X_{41}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{42}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{43}	(90,100)	(80,90)	(70,80)	(60,70)	<60
X_{44}	<2	(1.5,2)	(1,1.5)	(0.8,1)	<0.8
X_{45}	(90,100)	(80,90)	(70,80)	(60,70)	<60

Note: Descriptions of indicators are presented in Table 1.

cadmium, lead, and arsenic). To quantify the degree of pollution for these indicators, this study drew on relevant research results and divided the pollutants into several levels based on different concentration ranges. We then performed a standardized assessment based on the results of the ecological niche suitability model. The specific assessment criteria are shown in Table 6.

Although the ecological niche-based composite index differed from conventional single-dimension WQI measures, its construction was consistent with WQI practice in that water quality parameters were normalized, weighted, and aggregated based on both their environmental relevance and statistical variation across space and time. This allowed the composite index to reflect the relative contributions of different water-related indicators within the broader multi-media governance context.

Since the assessment index ranged from 0 to 1, the criteria for assessing the grade of the effect of synergistic management of environmental pollution in the Yellow River Basin can be determined as follows: $NS_{t\alpha}$ = [0.90,1.00]∈ Grade I, with an excellent assessment result; $NS_{t\alpha}$ = [0.80,0.90)∈ Grade II, with a good assessment result, $NS_{t\alpha}$ = [0.70,0.80), with a medium assessment result; $NS_{t\alpha}$ = [0.60,0.70), with a Pass; and $NS_{t\alpha}$ = [0,0.60), assessed as Fail.

4.3. Ecological niche suitability evaluation results

Based on the normalization of the assessment indicators, using the calculation results of $ANS_{t\alpha}$ and $RNS_{t\alpha}$ and the predetermined relative weights, Equation (9) was used to calculate the spatial ecological niche suitability of the synergistic management of environmental pollution in the Yellow River Basin. The specific calculation results are shown in Table 7.

From the above results, it is evident that the synergistic management of environmental pollution in the Yellow River Basin exhibited a clear trend of year-on-year improvement. In particular, since 2018, the assessment levels have all reached Level III or above, indicating a substantial improvement in governance effectiveness. Based on long-term field monitoring data on water, air, and soil quality compiled by environmental authorities in the Yellow River Basin (Tables 7-9), the composite governance index increased from approximately 0.60 in 2012 to about 0.85 in 2020, corresponding to an improvement of two to three ecological niche levels for most provinces. This evidence suggests that the coordinated governance measures implemented during this period have been associated with tangible improvements in environmental quality.

Similar to the absolute ecological niche model, the assessment results of the relative ecological niche model showed a trend of improvement every year. The relative ecological niche model was assessed at a low level in the early years, between Level V (fail) and Level IV (pass). However, from 2018 onwards, the assessment

Table 7. Assessment results of the absolute ecological niche model

Year	Assessment results	Assessment level
2012	0.6146	Level IV (pass)
2013	0.6039	Level IV (pass)
2014	0.6056	Level IV (pass)
2015	0.6198	Level IV (pass)
2016	0.6465	Level IV (pass)
2017	0.6856	Level IV (pass)
2018	0.7372	Level III (medium)
2019	0.8013	Level II (good)
2020	0.8778	Level II (good)

Table 8. Assessment results of the relative ecological niche model

Year	Assessment results	Assessment level
2012	0.5962	Level V (Failed)
2013	0.5858	Level V (Failed)
2014	0.5874	Level V (Failed)
2015	0.6012	Level IV (pass)
2016	0.6271	Level IV (pass)
2017	0.665	Level IV (pass)
2018	0.7151	Level III (medium)
2019	0.7772	Level III (medium)
2020	0.8515	Level II (good)

Table 9. Assessment results of the spatial ecological niche model

Year	Assessment results	Assessment level
2012	0.6054	Level IV (pass)
2013	0.5948	Level V (failed)
2014	0.5965	Level V (failed)
2015	0.6105	Level IV (pass)
2016	0.6368	Level IV (pass)
2017	0.6753	Level IV (pass)
2018	0.7261	Level III (medium)
2019	0.7892	Level III (medium)
2020	0.8646	Level II (good)

results gradually increased and finally reached the Level II (good) standard in 2020, further verifying the effectiveness of the synergistic management of environmental pollution in the Yellow River Basin.

Consistent with the results of the absolute ecological niche model and relative ecological niche model, the spatial ecological niche suitability model also showed a yearly increasing trend in the effectiveness of environmental pollution management in the Yellow River Basin. After 2018, the assessment level improved to Level III and subsequently reached Level II in 2020, indicating that the effect of coordinated management of environmental pollution in the Yellow River Basin has been significantly improved, and the ecological environment of the region has been significantly enhanced.

Figure 2 shows the time-series heat map of the comprehensive governance effectiveness index of the Yellow River Basin provinces in 2014, 2017, and 2020. From Figure 2, it can be seen that, over time, the overall comprehensive governance effectiveness of the Yellow River Basin provinces has shown a trend of continuous improvement. The governance effectiveness index of the upstream areas, such as Qinghai, Gansu, and other provinces, was always high (darker color), and the governance effectiveness of midstream areas (e.g., Shaanxi, Shanxi) and downstream provinces (Shandong, Hebei), which was relatively low in 2014, improved significantly by 2020. Additionally, the overall effectiveness of the Yellow River Basin gradually shifted from a low level to a higher level. Especially after 2017, the governance effectiveness index of Gansu, Qinghai, and Shaanxi provinces was significantly higher than in 2014, indicating that the relevant governance inputs and policy measures had begun to show results. Downstream provinces, such as Shandong and Hebei, have improved their governance effectiveness; however, progress in some areas has

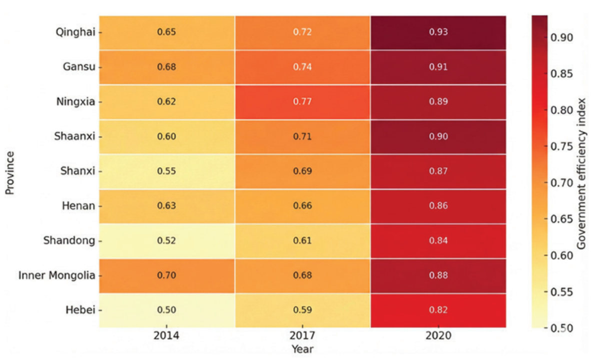

Figure 2. Governance efficiency index of Yellow River Basin provinces in 2014, 2017, and 2020

been relatively slow, and their governance performance remained at a moderately low level, with regional differences still evident. This is related to the distribution of ecological resources in the basin, which serves as the basis for pollution management, and the level of economic development. Overall, the heat map reveals the regional imbalance in the governance performance of the Yellow River Basin and the overall improvement in effectiveness brought about by coordinated governance in recent years. The years 2014, 2017, and 2020 were selected as representative cross-sections because they correspond to the early implementation phase, mid-term consolidation, and latest observation period of major national action plans on air, water, and soil pollution control, as well as the policy framework for ecological protection and high-quality development in the Yellow River Basin. Using these three benchmark years allowed the analysis to capture both the initial response and the cumulative effects of coordinated governance policies over time.

The upward trend in the governance index was consistent with the intensification of governance inputs from 2012 to 2020. In particular, the regression results in Table 4 indicate that higher environmental investment intensity and industrial structure upgrading are significantly associated with better governance performance, whereas high industrial pollution intensity has a negative impact. These findings suggest that increased investments in sewage treatment plants, industrial emission control facilities, and clean energy, combined with the phasing out of heavily polluting industries, have already begun to yield measurable improvements in basin-wide environmental quality.

To test the statistical significance of the improvement in governance effectiveness in the Yellow River Basin, this study further employed the nonparametric Bootstrap method to estimate CIs for the mean values of governance effectiveness in each province for 2014, 2017, and 2020. Based on samples from nine provinces each year, 95% CIs were constructed after repeated sampling (1,000 times). The results showed that the mean value of governance effectiveness was 0.617 (95% CI: 0.580, 0.654) in 2014, 0.687 (95% CI: 0.655, 0.714) in 2017, and 0.878 (95% CI: 0.861, 0.894) in 2020.

Figure 3 presents the mean governance efficiency index for the Yellow River Basin provinces in 2014, 2017, and 2020, along with the corresponding 95% bootstrap CIs. The results, based on 1,000 resamples, show a clear upward trend in efficiency over time, with no overlap between years, indicating statistically significant improvements in regional governance performance.

Bootstrap CIs for the difference in means between the three groups of years were as follows: 2014–2017 (+0.045, +0.123), 2017–2020 (+0.168, +0.219), and 2014–2020 (+ 0.215, +0.297), none of which contained zero, indicating statistically significant inter-annual variations. Thus, it can be further verified that the improvement of the effectiveness of coordinated governance in the Yellow River Basin during the 13th 5-year Plan period was not only evident in its upward trend but also statistically significant.

4.4. Spatial regression analysis

Considering the potential spatial correlation of inter-provincial synergistic management in the Yellow River Basin, this paper introduces the SDM based on the original regression model to extend the analysis. The results of the model estimation are presented in Figure 4. Both environmental investment intensity and industrial structure upgrading were significantly positively correlated with governance effectiveness ($p<0.05$), while the degree of industrial pollution and the pressure of urbanization had a significant negative impact on governance performance. The level of economic development exhibited a non-linear relationship, characterized by a negative coefficient for the primary term and a positive coefficient for the quadratic term, resulting in a U-shaped pattern that aligns with the Environmental Kuznets Curve hypothesis. In addition, the spatial lag term (i.e., the effect of governance effectiveness in neighboring provinces) was significantly positive ($p<0.01$), indicating that each province's governance performance was positively influenced by that of neighboring provinces, with a significant spatial spillover effect. This suggests that regional governance effectiveness not only depends on local factors but is also influenced by governance conditions in neighboring provinces, reflecting the externalities of synergistic governance. This result is consistent with the findings of Zhang[26]'s empirical study based on the Yangtze River Economic Belt, which emphasized the spatial transmissibility of pollution governance performance. Overall, the SDM results reveal the existence of a spatially correlated structure in governance performance, and policymakers should move beyond the single-province framework to construct a more integrated, regional synergy-oriented governance strategy.

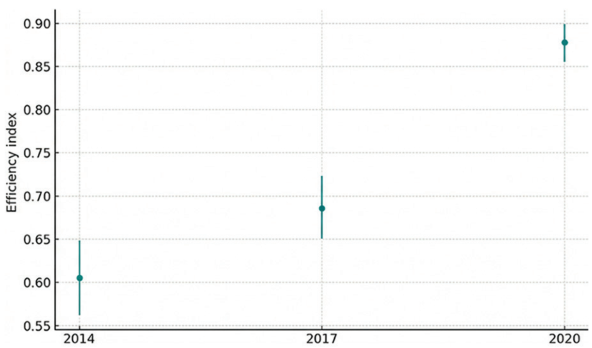

Figure 3. Governance efficiency means with 95% bootstrap confidence intervals

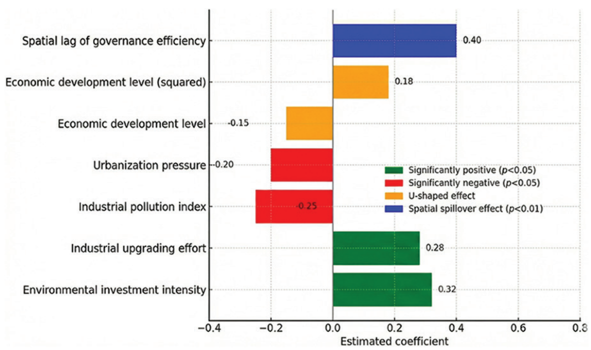

Figure 4. Main influencing factors and significance coefficients of the spatial Durbin model estimation

The horizontal bar chart visualizes the estimated coefficients of key influencing variables on regional governance efficiency, based on the results of the SDM regression. Green bars represent variables with a significantly positive effect ($p<0.05$), such as environmental investment and industrial upgrading. Red bars indicate significantly negative effects ($p<0.05$), including industrial pollution and urbanization pressure. Orange bars illustrate the U-shaped relationship with economic development, consistent with the Environmental Kuznets Curve hypothesis. The blue bar highlights the spatial lag term, indicating a strong and significant positive spillover effect ($p<0.01$), which suggests that one province's improvement in governance efficiency has a positive influence on its neighboring provinces.

Figure 5 presents the temporal evolution of average niche suitability across the Yellow River Basin from 2012 to 2020, reflecting the overall trend in coordinated governance efficiency. The results show a continuous upward trend, with statistically significant year-over-year improvements.

4.5. Economic significance and policy-relevant magnitudes

To complement statistical significance, it is important to interpret the magnitude of the estimated effects in terms of movements in the governance index and the

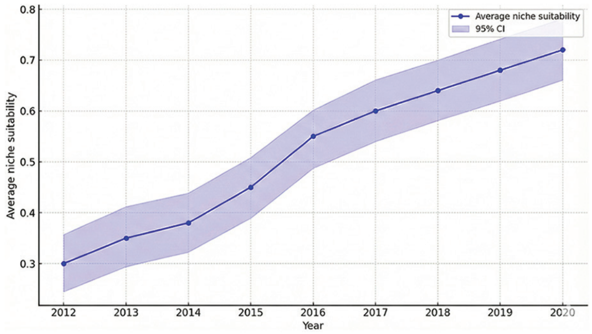

Figure 5. Trend of coordinated governance efficiency with 95% confidence intervals (2012–2020). The blue line represents the annual mean values, while the shaded area indicates the 95% bootstrap confidence intervals based on 1,000 simulations.

corresponding changes in ecological niche levels. Tables 7-9 show that the composite governance index for the Yellow River Basin increased from approximately 0.60 in 2012 to about 0.86 in 2020, corresponding to an improvement from Level V–IV (failed or barely qualified) to Level II (good) in most years. The threshold between Level IV and Level III was around 0.70, and the threshold between Level III and Level II was around 0.80. Therefore, a roughly 0.10 increase in the index was associated with one full level of improvement in governance performance.

The spatial regression results in Table 5 indicate that environmental investment intensity has a coefficient of 0.215 ($p<0.01$), and industrial structure upgrading has a coefficient of 0.189 ($p<0.01$), while industrial pollution intensity has a coefficient of −0.246 ($p<0.01$). This implies that, holding other factors constant, provinces with substantially higher environmental investment intensity or more advanced industrial structures can attain governance index values approximately 0.20 units higher, which is equivalent to roughly two ecological niche levels. Conversely, provinces with persistently high industrial pollution intensity may experience similar declines in governance performance. These magnitudes suggest that changes in key governance inputs have economically and environmentally meaningful impacts, rather than being merely statistically significant.

The spatial lag coefficient ($\rho=0.327$) was also economically significant. A one-unit increase in the average governance index of neighboring provinces raised the local index by approximately 0.33, corresponding to more than one-third of a level change. This finding highlights the importance of spillover effects: improvements in one province can partially transmit to neighboring provinces through shared river reaches, transboundary air flows, and coordinated policy actions. Therefore, cross-regional collaboration and joint prevention and control are not only statistically warranted but also substantively important.

Overall, the estimated magnitudes indicate that governance inputs and policy measures of realistic size—such as increasing environmental investment, upgrading industrial structure, and reducing industrial pollution intensity—can move provinces by one or more ecological niche levels within a decade. This provides a strong empirical basis for prioritizing these policy levers in the coordinated governance of environmental pollution in the Yellow River Basin.

4.6. Policy recommendations

The policy implications derived from our empirical results resonate with the broader evolution of climate and environmental governance in China. As summarized by Wu,[38] China's climate policy mix has gradually shifted toward more comprehensive, multi-level, and performance-oriented instruments. The coordinated pollution control system in the Yellow River Basin can benefit from similar principles by strengthening multi-level coordination mechanisms, improving the consistency of policy instruments, and embedding systematic *ex post* evaluation of governance performance into the policy cycle. The spatial spillover effects identified in this study further underscore the importance of cross-provincial coordination and joint assessment frameworks.

4.6.1. Strengthening of cross-regional synergistic governance and ecological compensation mechanisms

The management of environmental pollution in the Yellow River Basin requires a cross-provincial approach, and a coordinated management system should be established to address the challenges posed by single-province measures in coping with cross-regional pollution transmission. A closer inter-provincial coordinated management mechanism should be established and improved to further strengthen information sharing, policy alignment, and joint actions among the provincial governments in the Yellow River Basin. The significant positive spatial lag parameter ($\rho=0.327$, Table 4) indicates that improvements in governance performance in one province are associated with higher performance in neighboring provinces, underscoring the importance of cross-regional coordination, joint prevention and control, and ecological compensation mechanisms. At the same time, considering the differences in resource endowment, economic foundation, and environmental conditions in different regions, it is necessary to establish a reasonable regional ecological compensation mechanism, formulate compensation standards based on the environmental carrying capacity and pollution control pressure, support the restoration projects in ecologically fragile areas, and promote upstream, downstream, and inter-provincial coordination of interests, to provide a solid financial guarantee for cross-regional governance.

4.6.2. Optimization of emission standards and implementation of green development strategies

To effectively enhance the level of environmental governance in the Yellow River Basin, pollutant discharge standards should be continually improved, and supervision mechanisms should be strengthened, particularly in areas with severe cross-regional pollution. More stringent regional discharge standards should be formulated, and supervision should be strengthened to ensure the effective implementation of discharge control. The promotion of environmental technology research and development and innovation should be accelerated by supporting breakthroughs and applications in key areas, such as water purification, air pollution control, and soil remediation. Dedicated funding mechanisms should be established to promote the rapid development and deployment of high-efficiency environmental technologies. Policymakers should encourage the development of a green and circular economy by providing incentives for investment in environmental protection industries and green energy, and by supporting sustainable agriculture and environmentally friendly industries, thereby achieving ecological protection while promoting sustained and healthy economic development. The positive coefficients for environmental investment intensity (0.215) and industrial structure upgrading (0.189) and the negative coefficient for industrial pollution intensity (−0.246) highlight that strengthening emission standards, expanding investments in cleaner production and end-of-pipe treatment, and accelerating industrial upgrading are key policy levers that have already contributed to the observed improvements in governance effectiveness.

4.6.3. Differentiated regional actions and spillover-oriented coordination

Building on the finding that upstream provinces exhibit higher governance efficacy and that spatial spillovers are significant, the basin should adopt differentiated actions by river segment. Upstream provinces should consolidate demonstration effects by maintaining strict standards and transparent monitoring, sharing replicable enforcement toolkits with neighbors, and earmarking a fixed share of funds for inter-provincial co-projects such as joint monitoring stations and shared data platforms. Midstream provinces should prioritize industrial retrofitting with time-bound subsidies conditional on verified emission-intensity reductions, and harmonize standards in cross-border parks through formal information-sharing agreements. Downstream provinces should protect receptor zones by implementing hotspot-oriented controls at estuaries and industrial corridors, combining continuous monitoring with differentiated discharge fees and performance-based rebates, and integrating ecological restoration with end-of-pipe measures. Basin-wide, authorities should establish a coordination fund that prioritizes interventions with documented indirect effects, adopt a common monitoring, reporting, and verification platform, and synchronize enforcement calendars to raise collaboration quality. Progress should be tracked using measurable indicators, including the number of joint projects, changes in neighbors' efficacy and pressure indices, improvements in the synergy index, and compliance rates at receptor stations.

5. Conclusion

This study aimed to address three core questions regarding synergistic environmental pollution management in the Yellow River Basin: constructing a quantifiable evaluation index system, verifying spatial spillover effects, and identifying key influencing factors.

This study constructed a four-dimensional "drive–pressure–synergy–efficacy" index system and demonstrated its applicability using three ecological niche suitability models (absolute, relative, and spatial). The index system comprehensively covered socio-economic drivers (e.g., GDP per capita), pollution pressure (e.g., $PM_{2.5}$), cross-regional synergy (e.g., policy alignment), and governance efficacy (e.g., watershed compliance rate), thereby addressing the limitations of single-indicator or single-region evaluations in existing studies.

The SDM results confirmed that cross-provincial pollution control in the Yellow River Basin had a significant positive spatial spillover effect, as indicated by the spatial lag term (ρ=0.327, p<0.001). This means that pollution control inputs in one province not only improve its own governance efficiency but also have a positive impact on neighboring provinces, directly answering the second research question and supporting the necessity of transregional synergistic management.

Environmental investment intensity (coefficient = 0.215, p=0.002) and industrial structure upgrading (coefficient = 0.189, p=0.003) significantly promoted governance efficacy, while industrial pollution intensity (coefficient = −0.246, p=0.002) and urbanization pressure (coefficient = −0.178, p=0.006) exerted negative impacts. Spatially, upstream regions (e.g., Qinghai, Gansu) consistently showed higher governance efficacy than middle/lower reaches (e.g., Henan, Shandong), which reflects regional heterogeneity in suitability and provides a basis for differentiated policies.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data will be made available upon request to the corresponding author.

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