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Evaluation and External Driving Factors Analysis of Water–Energy–Food Resilience Security—Based on Spatial Durbin Model and Four Provinces Along the Yellow River

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Abstract: Research on water–energy–food security is crucial for ensuring the sustainable development of human society. Building on the water–energy–food theory and resilience concepts, a novel perspective termed "resilience security" was proposed. This differs from traditional approaches focused on coordination security and efficiency security. An indicator evaluation system consisting of 29 indicators was developed. Panel data from 2009 to 2022 in 40 cities across Shandong, Shanxi, Henan, and Shaanxi Provinces along the Yellow River were used to assess local water–energy–food resilience security. The nine external driving factors were empirically analyzed in different provinces using a spatial Durbin model. The findings indicate that: (1) over the 14-year period, the water—-energy–food resilience security of the sample transitioned from a near-exposure state to an initial resistance state; and (2) over the 14-year period, administrative power, market power, resource flow capacity, population density, industrial structure, urbanization level, scientific and technological inputs, environmental governance inputs, and spatial geographic factors significantly influenced regional water–energy–food resilience security, with notable variations across provinces.

Keywords: water–energy–food system; evaluation of resilience security; external driving factors analysis; spatial Durbin model

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1. Introduction

Water, energy, and food are the fundamental resources on which humans depend for their growth and survival, and strong interrelationships among the three have formed a linked water–energy–food system (the WEF-Nexus system). With the rapid growth of the global population, ecological degradation, and depletion of resource reserves, there is a severe shortage of water, energy, and food. As China is the world's largest consumer of the three resources, research on the security of its WEF-Nexus system is extremely important for ensuring the security of the resources of the country and those of the Asia-Pacific region.

Research on the security of the WEF-Nexus system primarily centers on two key aspects. One is coordination security, which aims to enhance the coordination among W, E, and F resources, thereby achieving a state of virtuous cycle and sustainable development [1–4]. The other is efficiency security, which seeks to improve the operational efficiency of the WEF-Nexus system, reducing resource loss and waste during its operation. This approach can help address the conflict between regional development and resource scarcity under various constraints, ultimately minimizing the risks in the supply–demand relationship of resources [5–9]. Researchers have studied WEF-Nexus system security by evaluating the coordination and efficiency, analyzing the influencing factors, and optimizing parameters [10–14].

The two primary research perspectives mentioned above focus on the endogenous security issues of the WEF-Nexus system while overlooking the disruptive factors continually emerging from human societal processes, such as natural disasters, geopolitical conflicts, and shifts in consumption patterns. These factors continually impact the system and have significant effects on its security status, posing a serious challenge to the resilience of the WEF-Nexus system. Several scholars have already emphasized, either directly or indirectly, the importance of resilience for essential resources like water, energy, and food. Specifically, Zhou et al. [15] and Ioannou et al. [16] highlighted that climate change is affecting the WEF-Nexus, with the latter emphasizing the need to enhance the resilience of the system to address global climate change. Núez-López et al. suggested that the WEF-Nexus system should be optimized from a resilience perspective [17]. Li et al. noted that the ongoing tension between resource supply and demand is placing continuous pressure on the system [18]. Gai et al. proposed that enhancing the adaptation of the WEF-Nexus system to external changes should be a future research direction, integrating existing studies on the WEF-Nexus [19], while Li et al. pointed out that recent events, such as the COVID-19 pandemic and geopolitical conflicts, have altered the global development pattern of the WEF-Nexus [20]. In conclusion, enhancing the resilience of the WEF-Nexus system in the face of external shocks, as well as ensuring quicker recovery and adaptation to changes after suffering damage, is critical for ensuring its sustainable operation. Although improving coordination security and efficiency security can increase the anti-jamming capabilities of the WEF-Nexus system to some extent, these perspectives do not incorporate the concepts of resistance and adaptation. Therefore, resilience security is proposed as a new entry point to broaden the research perspectives on the security of the WEF-Nexus and provide valuable references for policy formulation in this area.

Compared to the other two traditional perspectives, resilience security offers a richer connotation, particularly emphasizing the system's resistance and adaptation to external shocks [16,17,21,22]. It provides a more comprehensive measure of the security, stability, and sustainability of the WEF-Nexus system. However, academic research on WEF-Nexus resilience security remains limited. On the one hand, there is a lack of a clear definition of WEF-Nexus system resilience security, and on the other hand, most studies focus solely on the impact of specific external factors on the WEF-Nexus system. To address these gaps, a preliminary definition of WEF-Nexus resilience security is provided, and a comprehensive evaluation of the sample is conducted through the development of an indicator evaluation system to reflect its current status. Additionally, a comprehensive analytical model is constructed to accommodate the multiple external driving factors identified by scholars, aiming to verify their validity and explore their driving mechanisms.

2. Research Scope and Data Sources

China is the world's largest consumer of the three resources. The Yellow River Basin is a special geographical area in China that is rich in water, energy, and food resources, and the selection of cities within its boundaries for empirical research is extremely appropriate for the purpose of our study. Considering the stage of economic development of the region and the availability of data, all 40 cities along the Yellow River within the scope of Shandong, Shanxi, Henan, and Shaanxi Provinces are selected as the scope of the study, as shown in Table 1 and Figure 1.

Table 1. 40 cities along the Yellow River in Shanxi, Shaanxi, Henan, and Shandong.

Province	The Cities Along the Yellow River
Shanxi	Taiyuan, Datong, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzho, Linfen, Lvliang
Shaanxi	Xian, Tongchuan, Baoji, Xianyang, Weinan, Yanan, Yulin, Shangluo
Henan	Zhengzhou, Kaifeng, Luoyang, Anyang, Hebi, Xinxiang, Jiaozuo, Puyang, Sanmenxia, Shangqiu
Shandong	Jinan, Qingdao, Zibo, Dongying, Weifang, Jining, Taian, Dezhou, Liaocheng, Binzhou, Heze

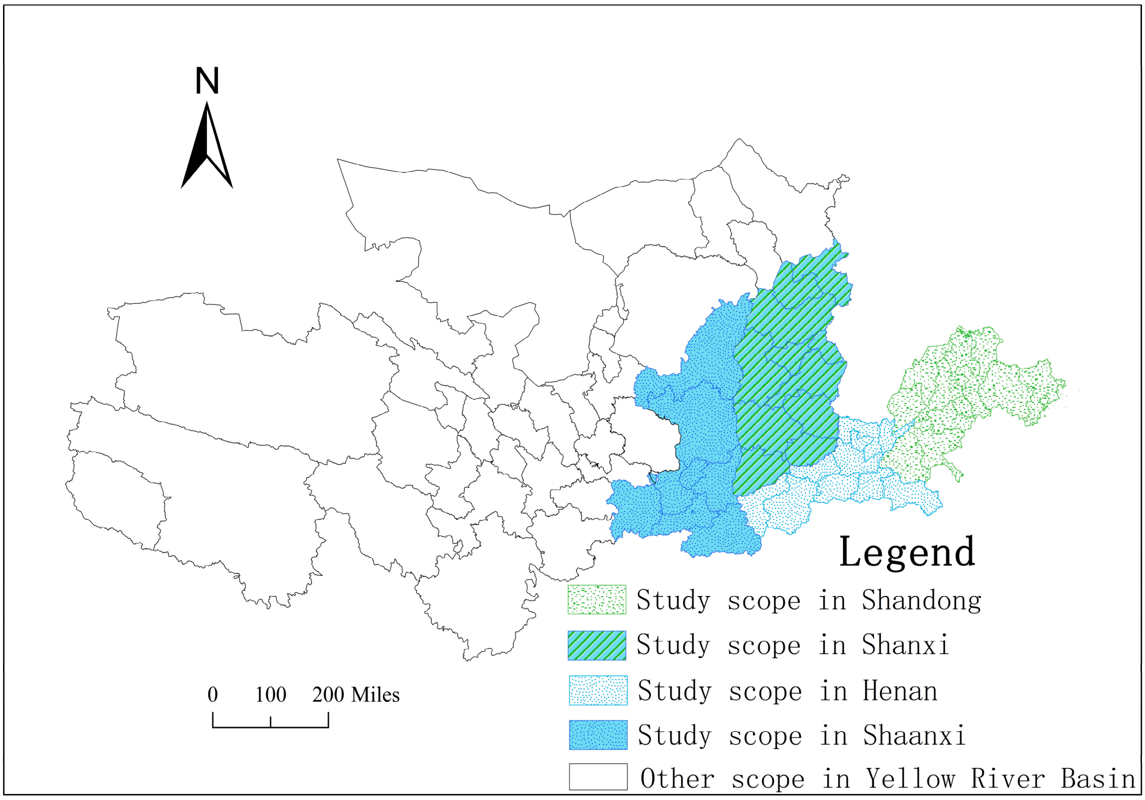

Figure 1. The map of the study scope within the Yellow River Basin.

All data used in this study were obtained from the China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, Yellow River Yearbook, local statistical yearbooks at the provincial level, local statistical yearbooks at the municipal level, water resource bulletins of provinces, statistical bureaus of provinces and municipalities, and China Glacier, Permafrost and Desert Science Data Centre for the years 2009–2022. To address the problem of missing and unavailable data, the mean value method or interpolation method was used to complete the data according to the actual situation, and the outliers in each year were rationalized according to the trend recorded in the previous years.

3. Definition of the Concept of WEF-Nexus System Resilience Security

According to one of the research ideas on the security of the WEF-Nexus system, one of the three core resources of the WEF-Nexus system can be considered a baseline resource, whereas the remaining two resources can be considered associated paths [23]. Based on this idea, we considered WEF-Nexus system resilience security as an extension and expansion of energy system resilience and then defined the concepts of WEF-Nexus system resilience security by taking the existing concepts related to energy system resilience as a baseline and combining them with WEF-Nexus theory and resilience theory.

The WEF-Nexus theory consists of three main points. The first point involves water, energy, and food, as basic resources, which are slow variables for regional sustainable development and are each other's 'short boards'. If these three resources are in short supply, then other resources, even if abundant, cannot ensure the development of the region, and this perspective is called the 'slow variable view'. Second, from the perspective of resource management, a strong correlation and mutual feedback effect exists among water, energy, and food. It is based on a single resource, and the study of the two correlations can mislead decision-making and cannot support the development and implementation of related policy programs; this view is called the 'resource integration view' [24]. The third is the 'core–periphery relationship' structure, where the core system consists of the water subsystem, the energy subsystem, and the food subsystem, reflecting the linkages and operation of the three resources, whereas the periphery system consists of the social subsystem, the economic subsystem, and the environmental subsystem, reflecting the impacts of external driving factors on the WEF Nexus [18,25]. To summarize, WEF-Nexus theory emphasizes the holistic, coordinated, systemic nature of these three resources and the impact of external drivers on the system.

Some representative views on the concept of energy system resilience are presented below. Sharifi et al. summarized the literature on the terms 'energy' or 'resilience' and reported that 'preparation', 'absorption', 'recovery', and 'adaptation' were the most frequently occurring terms [26]. This view is most recognized in academia. Based on this, scholars have proposed that the long-term security of the energy system depends on its supply and demand, production, transport, distribution, transformation, and other capabilities [27–30]. Chen Sai et al. summarized the previous views and highlighted the "four-stage" nature of energy system resilience in response to external shocks [21].

In summary, the concept of WEF-Nexus system resilience security should involve the following six elements, as shown in Table 2.

Table 2. Six elements should be involved in the concept of WEF-Nexus system resilience security.

Elements	Connotation
Supply–demand relationships	Refers to the adaptability and balance between the supply side and the demand side of resources.
Principle of coordination and equality	Requires that the three resources be coordinated and equal in status.
Core–periphery relationships	The core represents the internal relationships among the three resources, and the periphery represents the factors that will drive the internals, mainly social, economic, and environmental factors.
Four-stage capacity	Refers to the system's ability to prepare, absorb, recover, and adapt, which can be viewed as a decomposition of the WEF-Nexus system's resilience security and together determine its value.
Geographical constraints	According to the New Economic Geography Theory, there are significant differences in the WEF-Nexus system across regions [5].
Targets	Achieving long-term stability and sustainability in the supply and demand relationship for the three resources.

According to the concept of energy system resilience and Table 2, this study provided a preliminary definition of the concept of WEF-Nexus system resilience security, which is the ability of the three resources in the system to coordinate with each other and maintain a stable supply–demand relationship in the long term by improving the capacity of each subsystem in the four phases of preparation, absorption, recovery, and adaptation when it is subjected to external shocks, fully accounting for the relevance of water, energy, and food. The elements in Table 2 and their relationships with each other were further transformed into a conceptual diagram, as shown in Figure 2, where the direction of the arrows indicate the direction of influence.

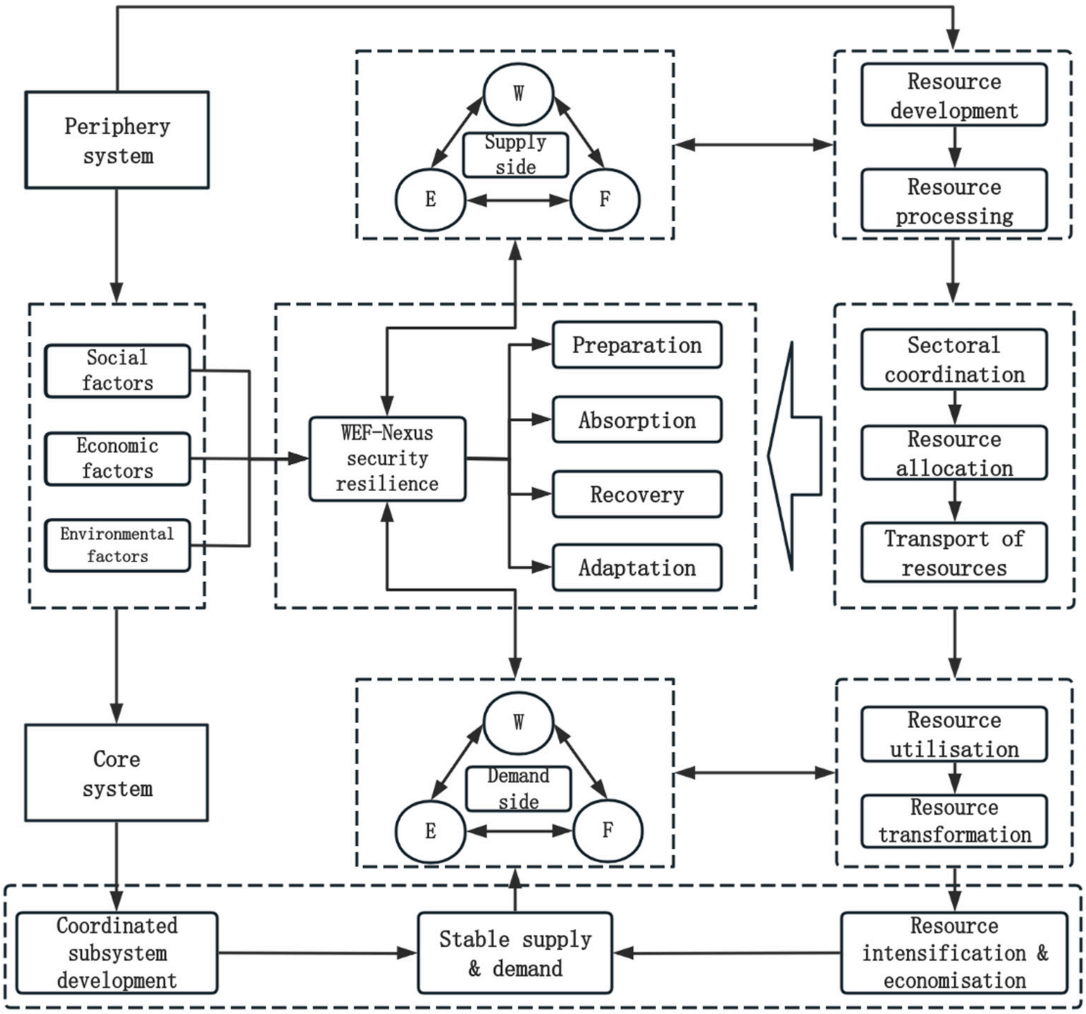

Figure 2. The conceptual diagram of WEF-Nexus system resilience security.

4. Method

4.1. Construction of an Indicator System for WEF-Nexus System Resilience Security

Based on the definition of WEF-Nexus resilience security in this study, an indicator evaluation system was established. The specific steps are as follows:

Step 1: The dimensions of the indicator system for WEF-Nexus resilience security were classified into a target layer, a guideline layer, and an indicator layer.

Step 2: According to resilience theory, the target layer was defined as the preparation, absorption, recovery, and adaptation capabilities of each subsystem (the connotations of these four capacities are detailed in Table 3).

Step 3: The objective layer was decomposed into a guideline layer based on the connotations of the four capabilities and the characteristics of the supply and demand relationship for each resource.

Step 4: Quantitative indicators that reflect the characteristics of the guideline layer were selected for the indicator layer. In this study, 41 relevant indicators were summarized from numerous studies on the assessment of water, energy, and food security [1–18,31–33], following the principle of including as many indicators as possible. Considering data accessibility, the appropriateness of the research samples, and ensuring no overlap in the information through a correlation test of the indicators, 29 out of 41 were ultimately selected to construct the indicator evaluation system. The specific content is provided in Table 4, with the calculation method of each indicator and the source of the original data detailed in Table 5.

Table 3. Description of the capabilities of the WEF-Nexus system resilience security phases.

Phase Capacity	Description of Connotation
Preparation	Preparation is the initial operating state of the system before it is subjected to external shocks; it is shock-resistant to some extent. Generally, the greater the overall operating state of the system, i.e., the higher the efficiency of resource production and utilization, the stronger its ability to withstand shocks.
Absorption	Absorption is the ability of a system to maintain as normal a relationship between the supply of and demand for resources as possible while being weakened by a complete shock. Generally, the more self-sufficient and reserved the resource system, i.e., the better the resource redundancy, the greater the absorptive capacity of the system.
Recovery	Recovery is the rate at which a system recovers to the initial steady state of supply and demand for the three resources after the lowest level of decline in its functioning due to an external shock. It is closely related to labor and fixed capital, and it is generally accepted that the more timely and efficient the recovery of the functions of the system, the stronger the recovery capacity of the system.
Adaptation	After the system recovers from an external shock, it undergoes internal regulation and reorganization so that its functions improve to better cope with the ability of the next shock. Generally, the better the final state of functioning of the system, the better the adaptive capacity of the system.

Table 4. Indicator evaluation system of WEF-Nexus system resilience security.

Subsystem	Target Layer	Guideline Layer	Indicator Layer (No.)	Nature
Water	Preparation	State of total water resources	Water resources per capita (1)	Positive
		State of water use efficiency	Intensity of water consumption (2)	Negative
		State of water productivity	Coefficient of Storage (3)	Positive
	Absorption	Water resource self-sufficiency	Total water resources redundancy (4)	Positive
	Recovery	Water resources production labor force	Number of persons employed in the production and supply of electricity, heat, water, and gas (5)	Positive
		Fixed capital for Water production	Length of district water pipelines (6)	Positive
	Adaptation	Environmental adaptability	Sewage treatment rate (7)	Positive
			Sewage discharge (8)	Negative
		Dosage adaptability	Water reuse rate (9)	Positive
Energy	Preparation	State of energy production	Primary energy production per capita (10)	Positive
		State of energy use efficiency	Energy consumption intensity (11)	Negative
		State of energy productivity	Percentage of energy consumption in the secondary sector (12)	Negative
	Absorption	Status of energy reserves	Reserve-production ratio (13)	Positive
		State of energy self-sufficiency	Rate of energy self-sufficiency (14)	Positive
	Recovery	Energy production labor force	Total number of employees in the scale energy sector (15)	Positive
		Fixed capital for energy production	Total fixed assets of enterprises in the large-scale energy industry (16)	Positive
	Adaptation	Environmental adaptability	Industrial emissions (17)	Negative
			Industrial wastewater discharge (18)	Negative
		Consumption adaptability	Energy consumption elasticity coefficient (19)	Negative
		Dosage adaptability	Reduction rate of energy consumption of 10,000 Yuan GDP (equivalent value) (20)	Positive

Table 4. *Cont.*

Subsystem	Target Layer	Guideline Layer	Indicator Layer (No.)	Nature
Food	Preparation	State of efficiency of food production	Yield per unit of sown food area (21)	Positive
		State of efficiency in the use of arable land	Ratio of effectively irrigated agricultural land (22)	Positive
	Absorption	State of food self-sufficiency	Per capita yield of grain (23)	Positive
		State of land use	Cultivated land area redundancy (24)	Positive
	Recovery	Labor force for food production	Total number of employees in agriculture (25)	Positive
		Fixed capital for food production	Total mechanical power per unit of sown area of crops (26)	Positive
	Adaptation	Environmental adaptability	Fertilizer load (27)	Negative
		Consumption adaptability	Engel's coefficient (28)	Negative
			Prices indices of food (29)	Negative

Table 5. Calculation method and source of each indicator.

No. of the Indicator	Calculation Method and Source
(1)	Ratio of total water resources ⑥ to total population ①
(2)	Ratio of total water consumption ⑥ to GDP ①
(3)	Statistical data ⑥
(4)	Ratio of water resources per capita ⑥ to consumption ⑥
(5)	Statistical data ②
(6)	Statistical data ②
(7)	Statistical data①
(8)	Statistical data ①
(9)	Statistical data ①
(10)	Ratio of total primary energy production ④ and ⑧ to total population ①
(11)	Ratio of total energy consumption ④ and ⑧ to GDP ①
(12)	Ratio of energy consumption in the secondary sector ④ and ⑧ to total energy consumption ④ and ⑧
(13)	Ratio of primary energy proved reserves ⑧ to total production ④ and ⑧
(14)	Ratio of total primary energy production ④ and ⑧ to total energy consumption ④ and ⑧
(15)	Statistical data ⑧
(16)	Statistical data ⑧
(17)	Statistical data ① and ②
(18)	Statistical data ① and ②
(19)	Calculated by the corresponding formula
(20)	Statistical data ④ and ⑤
(21)	Ratio of total food production ④ and ⑤ to total sown area ④ and ⑤
(22)	Ratio of irrigated cropland area ④ and ⑤ to total cropland area ④ and ⑤
(23)	Ratio of total food production ④ and ⑤ to total population ④ and ⑤
(24)	Ratio of area sown with food ④ and ⑤ to total area of the region ④ and ⑤
(25)	Statistical data ③, ④ and ⑤
(26)	Ratio of total power of agricultural machinery ④ and ⑤ to area sown with food ④ and ⑤
(27)	Ratio of net discounted fertilizer use ④ and ⑤ to area sown with food ④ and ⑤
(28)	Calculated by the corresponding formula
(29)	Statistical data ⑦

Note: ①–⑧ represent data sources. ①: China Urban Statistical Yearbook. ②: China Urban Construction Statistical Yearbook. ③: Yellow River Yearbook. ④: Local statistical yearbooks at the provincial level. ⑤: Local statistical yearbooks at the municipal level. ⑥: Water resource bulletins of provinces. ⑦: Statistical bureaus of provinces and municipalities. ⑧: China Glacier, Permafrost, and Desert Science Data Centre.

4.2. Measurement Method of the Indicator Evaluation System

Referring to the methods used by scholars to evaluate the security of the WEF-Nexus system, this study measures the level of WEF-Nexus system resilience security in cities along the Yellow River in Shandong, Shanxi, Henan, and Shaanxi. First, to exclude the influence of subjective factors, the entropy weight method was used to calculate the assessment values of the water resource subsystem, energy subsystem, and food subsystem. Second, the assessment values of the three subsystems were coupled using the coupled coordination model to obtain the final results of the WEF-Nexus system resilience security, as follows:

Step 1: All the data are standardized via the extreme variance method to ensure consistency in the measurement of all the indicators, and X_{ij} is the standardized value of indicator j of city i.

Step 2: For each subsystem, there are m samples to be evaluated, and each sample corresponds to n evaluation indicators, constructing a m $\times$ n data $_{matrix}$ $(X_{ij})_{m\times n}$.

Step 3: Calculate the information entropy e_j for indicator j as follows:

$$e_j = -1/\ln m \sum_{i=1}^{m} P_{ij} \ln P_{ij} \tag{1}$$

where P_{ij} is the weight of indicator j of city i, which is calculated as follows:

$$P_{ij} = X_{ij} / \sum_{i=1}^{m} X_{ij} \tag{2}$$

Step 4: Calculate the weights w_j for indicator j as follows:

$$w_j = (1 - e_j) / \sum_{j=1}^{n} (1 - e_j) \tag{3}$$

Step 5: Calculate the combined evaluation value R_i of each subsystem as follows:

$$R_i = \sum_{j=1}^{n} w_j X_{ij} \tag{4}$$

Step 6: The coordination of each subsystem is an important link in determining its overall resilience security level, and we use a coupled coordination model to comprehensively measure the WEF-Nexus system resilience security level with the following formula:

$$R_{WEF} = \sqrt{C_{WEF} \cdot [\alpha_1 R_w + \alpha_2 R_E + \alpha_3 R_F]} \tag{5}$$

$$C_{WEF} = \left\{ \frac{R_W \cdot R_E \cdot R_F}{[R_W + R_E + R_F]^n} \right\}^n \tag{6}$$

where R_{WEF} is the comprehensive evaluation value of the WEF-Nexus system resilience security in a region; R_W, R_E, and R_F correspond to the resilience security levels of the water resource subsystem, the energy subsystem, and the food subsystem, respectively, from R_i in step 6; α_1, α_2, and α_3 are the coefficients that are set to one-third according to the principle of equality in WEF-Nexus system theory; C_{WEF} is the coupling index of each subsystem's resilience security; and the number of subsystems in this study is 3, so n = 3 is used. Table 6 shows the measurement results of the WEF-Nexus system resilience security of the study area in several years of the 14-year period.

Table 6. Measurement results of WEF-Nexus system resilience security.

Year \ Region	2009	2012	2015	2018	2022
Shanxi	0.3571	0.3745	0.3750	0.3918	0.4002
Shandong	0.3979	0.4282	0.4384	0.4608	0.4913
Henan	0.3635	0.3812	0.4169	0.4002	0.4147
Shaanxi	0.3572	0.3883	0.3827	0.3972	0.4101

Based on the calculation principle of the coupled coordination model, the results can be classified into six resilience grades [3,8]: when R∈(0, 0.2], the system is in an exposed state; when R∈(0.2, 0.4], the system is in a near-exposure state; when R∈(0.4, 0.5], the system is in a barely resistant state; when R∈(0.5, 0.6], the system is in an initial resistant state; when R∈(0.6, 0.8], the system is in an medium resistant state; and when R∈(0.8, 1.0], the system is in an advanced resistant state. As shown in Table 5, the entire study sample demonstrates a trend of change from a near-exposed state to a barely resistant state over the 14-year period, while the cities along the Yellow River in Shandong are very close to an initial resistant state in 2022.

4.3. Construction of an Analytical Model for External Drivers of the WEF-Nexus System Resilience Security

To explore the driving mechanism of WEF-Nexus system resilience security, we empirically analyzed the external driving factors of WEF-Nexus system resilience security by constructing an econometric model on the basis of the measurement results of the constructed indicator evaluation system and the theory of the core–periphery relationship.

4.3.1. Selection of External Driving Factors

We organized and summarized existing research on the external driving factors of the WEF-Nexus system, and the more representative views are described below. Hoff, who developed the WEF-Nexus theory, proposed at the Bonn conference that the external factors of the WEF-Nexus system include the social, economic, and environmental dimensions. The social dimension involves accelerating the construction of the social substrate and controlling population growth, the economic dimension emphasizes the need to transform the results of economic development into the efficient use of resources, and the environmental dimension emphasizes the need to invest in the maintenance of ecological system stability [34]. In the same year, the Stockholm Institute suggested that the external driving factors of the WEF-Nexus system were derived mainly from social and natural systems; social systems included regional population growth, urbanization, financial crises, and overutilization of resources, whereas natural systems included elements such as climate change and environmental variability [35]. Based on this, Conway et al. further divided the external influences of the WEF-Nexus system into direct and non-direct factors. The direct factors mainly were the long-term, trending effects of climate change, whereas the non-direct factors included economic growth, demographic issues, and scientific and technological advancements [36]. From an adaptive perspective, Rasul and Sharma identified economic efficiency, social equity, and environmental sustainability as the main external factors affecting the WEF-Nexus system [25]. Li et al. argued that the external effects of the WEF-Nexus system should be focused on the supply and demand sides, with the demand side being mainly influenced by social system factors such as regional economic development, population growth, and urbanization, and the supply side being influenced by ecosystem factors [20]. Additionally, some researchers have also specified the ways to influence the WEF-Nexus system in terms of change of climate [15,16], government strategy [37], carbon emission [38], urbanization process [39–41], infrastructure [42], industrial structure [43].

To summarize, the external driving factors of the WEF-Nexus system are centered mainly around 'social', 'economic', and 'environmental' aspects, which also match the views expressed in the classic panorama of the WEF-Nexus proposed by Hoff [34]. Therefore, this article summarized the types of external driving factors of WEF-Nexus system resilience security in terms of social, economic, and environmental factors, and considering the availability of data, eight external driving factors were selected from the above literature as the main research objects of this study, including population density, urbanization level, scientific and technological inputs, administrative power, market power, industrial structure, resource flow capacity, and environmental governance inputs. When researchers discuss the external effects of the WEF-Nexus system, they mention terms such as 'region' and 'geo' very frequently, which emphasizes that the WEF-Nexus system is affected not only by the above three types of factors but also by the spatial geography. Thus, spatial geography is an important part of the process of evaluating the external drivers of WEF-Nexus system resilience security.

In summary, we empirically investigated the external driving factors of WEF-Nexus system resilience security within the scope of this study using a spatial econometric model, and the specific drivers and their measurable indicators are shown in Table 7.

Table 7. Selection and measurable indicators of external driving factors.

Type of Factors	Driving Factor	Measurement Indicator
Social factors	Population density	The ratio of the total resident population of the region ① to the land area of the administrative region ⑦
	Urbanization level	The total regional urban population ① as a proportion of the total resident population ①
	Scientific and technological inputs	Total regional R&D expenditure ②, ④ and ⑤
Economic factors	Administrative power	Total regional government public finance expenditures as a share of GDP ① and ②
	Market power	Total regional retail sales of consumer goods ④ and ⑤
	Industrial structure	GDP ① and ② of the secondary sector as a share of regional GDP ⑦ and ⑧
	Resource flow capacity	Total regional cargo turnover ①, ④ and ⑤
Environmental factors	Environmental governance inputs	Total investment in regional environmental pollution control ①, ② and ⑧
Spatial geographic factors	Regional differences	Regressions coefficients and parameters in spatial econometric model

Note: ①–⑧ represent data sources. ①: China Urban Statistical Yearbook. ②: China Urban Construction Statistical Yearbook. ③: Yellow River Yearbook. ④: Local statistical yearbooks at the provincial level. ⑤: Local statistical yearbooks at the municipal level. ⑥: Water resource bulletins of provinces. ⑦: Statistical bureaus of provinces and municipalities. ⑧: China Glacier, Permafrost, and Desert Science Data Centre.

4.3.2. Construction and Test of the Spatial Econometric Models

Based on the empirical demand, the WEF-Nexus system resilience security was set as an explained variable in this article, and the selected external driving factors were used as explanatory variables. Among them, the measurements of the explanatory variables were present in the original data indicators with large differences in values and in the ratios of heavy indicators with small differences in values, which may lead to the emergence of model heteroscedasticity when the variables are regressed directly. Thus, we used the logarithmic value of all the indicator data to avoid model heteroscedasticity.

On the basis of the general process of spatial econometric modeling, the process of the model tests is as follows:

Step 1: The presence of spatial effects in the study objects was determined using Moran's I method.

Step 2: The experimental data all met the robustness requirements, with first-order differencing determined using the LLC test.

Step 3: The spatial Durbin model was selected among the three common spatial econometric models (spatial lag, spatial error, and spatial Durbin) using the Lagrange multiplier test (LM test).

Step 4: The spatial econometric model was used for the two effects (fixed effects, random effects) of the fixed effects, which were determined using the Hausmann test. Then, we used all three fixed effects (time fixed effects, spatial fixed effects, and double fixed effects) for the data regression and found that the double fixed effects can yield the most satisfactory results.

Step 5: The constructed double fixed effects spatial Durbin model was determined to be nondegradable to a spatial lag model and a spatial error model using the Wald test and the likelihood ratio test.

Step 6: Finally, we determined the double-fixed spatial Durbin model to analyze the external driving factors of the regional WEF-Nexus system resilience security. The model is shown below:

$$\begin{aligned} \ln RES_{it} = \beta_0 + \rho \textstyle\sum_{j=1}^{n} W_{ij} \ln RES_{jt} + \beta_1 \ln DEN_{it} + \beta_2 \ln URB_{it} + \beta_3 \ln TEC_{it} + \beta_4 \ln GOV_{it} \\ +\beta_5 \ln MAR_{it} + \beta_6 \ln IND_{it} + \beta_7 \ln FLO_{it} + \beta_8 \ln ENV_{it} + \delta \textstyle\sum_{j=1}^{n} W_{ij} (\ln DEN_{jt} \\ + \ln URB_{jt} + \ln TEC_{jt} + \ln GOV_{jt} + \ln MAR_{jt} + \ln IND_{jt} + \ln FLO_{jt} + \ln ENV_{jt}) \end{aligned} \quad (7)$$

where RES_{it} denotes the explained variable of the model and denotes the level of the WEF-Nexus system resilience security in year t of region i; DEN_{it}, URB_{it}, TEC_{it}, GOV_{it}, MAR_{it}, IND_{it}, FLO_{it}, and ENV_{it} denote the corresponding measures of population density, urbanization level, scientific and technological inputs, administrative power, market power, industrial structure, resource flow capacity, and environmental governance inputs in year t of region i, respectively; W_{ij} denotes a spatial weight matrix based on the inverse of the geographic distance in latitude and longitude for areas i and j; $WijlnRES_{jt}$ denotes the interaction effect between the local explained variables and the neighbor's explained variables; $W_{ij}(lnDEN_{jt} + lnURB_{jt} + \ldots + lnENV_{jt})$ denotes the interaction effect of local explained variables with neighbor's explanatory variables; δ denotes the coefficient to be determined for the neighbor's explanatory variables; μ_i and v_t denote the individual and time effects of the panel model, respectively; ε_{it} denotes the random perturbation term in year t of region i; β_n denotes the coefficient to be determined; and ρ denotes the spatial autoregressive coefficient.

5. Results and Analysis

We constructed an external driver analysis model of WEF-Nexus system resilience security to analyze the four provinces along the Yellow River over the 14-year period. The model regression results are shown in Table 7. The meaning of the information in the table is shown below:

'Direct effect' represents the effect of each local driving factor on the local WEF-Nexus system resilience security.

'Indirect effect' represents the effect of each driving factor in areas neighboring the local area on the local WEF-Nexus system resilience security, i.e., the spatial geographic factor effect in this study.

'Total effect' represents the superimposed impact effect of the first two effects.

Positive and negative cases represent positive and negative effects, respectively.

The value n represents that for every percentage point at which the corresponding variable is raised, the explained variable is also raised by n percentage points.

The analysis based on Table 8 is as follows:

Table 8. Model regression results for the four provinces along the Yellow River.

Variable	Effect	GOV	MAR	IND	FLO	DEN	URB	TEC	ENV
SD	Direct effect	−0.75 ***	0.27 **	NS	NS	0.22 *	NS	1.67 ***	1.94 ***
	Indirect effect	NS	1.69 **	1.58 ***	NS	NS	NS	NS	NS
	Total effect	NS	1.95 **	1.94 ***	NS	NS	NS	NS	NS
SX	Direct effect	−0.42 **	−0.40 **	−0.29 *	NS	NS	0.77 **	NS	−2.08 **
	Indirect effect	NS	−0.43 ***	1.50 *	NS	NS	1.47 **	NS	−3.01 **
	Total effect	NS	−0.82 ***	NS	NS	NS	2.24 **	NS	−5.09 **
HN	Direct effect	0.42 *	0.24 **	0.94 ***	NS	NS	NS	NS	NS
	Indirect effect	NS	NS	NS	NS	−1.27 ***	NS	NS	NS
	Total effect	NS	NS	1.18 **	NS	NS	NS	NS	NS
SaX	Direct effect	NS	−0.64 **	1.00 ***	1.20 ***	0.77 ***	−0.59 **	NS	NS
	Indirect effect	NS	NS	0.35 *	NS	1.20 *	0.74 **	NS	NS
	Total effect	NS	NS	1.35 ***	NS	1.97 **	0.16 ***	NS	NS

'*, ** and ***' indicate that the driving factors hold at the 10%, 5% and 1% significance levels, respectively, i.e., the variable's influence effect can be considered real. 'NS' represents that there is no significant influence effect. 'SD, SX, HN, and SaX' represent the cities along the Yellow River in Shandong, Shanxi, Henan, and Shaanxi, i.e., the research scope of this paper; see 'Research Scope and Data Sources' for details.

5.1. Analysis of the Cities Along the Yellow River in Shandong

The market power (MAR) on WEF-Nexus system resilience security was significantly positive at the 5% level, and for every 1 percentage point increase in MAR in the local and neighboring regions, the level of WEF-Nexus system resilience security increased by 0.27 and 1.69 percentage points, respectively, the reason could be that the favorable market atmosphere in Shandong Province further strengthened the efficiency of market mechanisms in allocating WEF-Nexus resources and optimized the four capabilities of WEF-Nexus resilience security.

For administrative power (GOV), for every 1 percentage point increase in local administrative power, the WEF-Nexus system resilience security decreased by 0.75 percentage points, indicating that for the more economically developed Shandong Province, an increase in government-led power instead inhibited the efficient resource allocation situation originally led by the market, which in turn had downward pressure on the supply and demand stability of the WEF-Nexus system.

The indirect and total effects of the industrial structure (IND) were both significantly positive. The reason could be due to the high level of modernization of Shandong's overall industry because an increase in the proportion of secondary industry in neighboring regions will have a supportive effect on the local resource supply capacity, which in turn can improve the four capacities of WEF-Nexus system resilience security.

The direct effect of population density (DEN) was significantly positive, which illustrated that the population carrying capacity in Shandong was better, and the appropriate amount of population growth was favorable for improving the four capacities of the WEF-Nexus system resilience security.

For technology inputs (TEC), which are insignificant in all other regions, and environmental governance inputs (ENV), which are significant and negative only in Shanxi, both show positive direct effects at the 1% significance level with coefficients of 1.67 and 1.94, respectively, which indicated that TEC and ENV in Shandong achieved better results. This study argues that, on the one hand, Shandong had a good socioeconomic foundation, and the injection of technological capital can effectively promote the accumulation of human and technological capital, which in turn breaks through the threshold of high-tech production technology and realizes the incremental increase in resource productivity and utilization efficiency, thus optimizing the four capabilities of WEF-Nexus resilience security. On the other hand, the realization of high-tech production technology will also ease the contradiction between economic development and overexploitation of resources, reduce the difficulty of environmental governance, and enhance the effect of environmental governance. Thus, the ENV in Shandong can have a positive effect on the WEF-Nexus system resilience security.

5.2. Analysis of the Cities Along the Yellow River in Shanxi

The direct effect of GOV on WEF-Nexus system resilience security was significantly negative at the 5% level, whereas MAR was also significantly negative at all three effects, indicating that the combined effect of local government control policies and market mechanisms does not positively affect local WEF-Nexus system resilience security. The reason could be that in Shanxi Province, which is the energy base of China, the price of its energy is strictly controlled by the government. Thus, the market mechanism in the region cannot play its true role, coupled with the crude mode of resource exploitation and utilization and the untimely extension of the industrial chain, which leads to the development of unhealthy market-oriented development, causing the regression situation of the four capacities of WEF-Nexus system resilience security.

The direct and indirect effects of the IND were in the opposite directions at the 10% significance level, and for every 1 percentage point increase in the proportion of the secondary industry in the local and neighboring regions led to a decrease and increase in the WEF-Nexus system resilience security by 0.29 and 1.50 percentage points, respectively, the reason could be that Shanxi is still in the mode of rough development that is highly dependent on coal resources. The overall secondary industry of the province is heavily biased toward mining and low-end manufacturing, the level of industrialization is not as high as the data seems, the local energy industry is less efficient in production, the use of water resources is inefficient, the pollution situation is more serious, and these weakened the four capacities of WEF-Nexus system resilience security.

All three effects of urbanization level (URB) were significantly positive at the 5% level, indicating that promoting urbanization in Shanxi can effectively improve the WEF-Nexus system resilience security. The reason could be that optimizing and promoting the quality and process of urbanization development can effectively solve the problems of urban–rural segmentation and an unbalanced distribution of agricultural and industrial labor in resource-dependent regions, which in turn affects the capacities of preparation and recovery.

There were some abnormal conditions in which the three effects of ENV were all significantly negative and with larger coefficients. The reason could be that the rate of environmental restoration lags behind the rate of environmental destruction, and the coefficient of the indirect effect is higher than that of the direct effect, which indicates that there may be an effect of environmental pollution and overexploitation of resources, which is a ‘competition at the bottom’.

5.3. Analysis of the Cities Along the Yellow River in Henan

The direct effects of GOV and MAR on WEF-Nexus system resilience security were significantly positive, and for every 1 percentage point increase in the level of local GOV and MAR, the level of WEF-Nexus system resilience security increased by 0.42 and 0.24 percentage points, respectively, which indicated that the government and market jointly coordinate and stabilize the supply and demand relationship of the regional WEF-Nexus system. However, their indirect effects are both not significant, which suggests that the linkage between the regions needs to be improved.

The direct and total effects of IND were significantly positive, indicating that the overall structure of industrial and agricultural is relatively reasonable, there is no transitional dependence on the resource industry, and the manufacturing industry in the secondary industry optimizes the four capacities of WEF-Nexus system resilience security.

The indirect and total effects of DEN are both significantly negative at the 1% level, indicating that for Henan Province, which has a large population, rapid population growth has increased the mismatch between supply and demand in the WEF-Nexus system, which is not conducive to maintaining a stable supply and demand relationship in the WEF-Nexus system over the long term.

5.4. Analysis of the Cities Along the Yellow River in Shaanxi

The direct effect of MAR on the WEF-Nexus system resilience security was significantly negative. The reasons could be that Shaanxi is limited by its westward geographic location in China, the regional economic base is relatively weak, marketization starts late, the market mechanism is immature, and the capacity of resource allocation in this region is limited, which weakened the four capacities of the WEF-Nexus system resilience security.

The GOV did not show a significant effect, indicating that the government's policy implementation effect is not strong and does not play a key role in regulating the market mechanism.

As Shanxi is the only region where a significant effect of resource flow capacity (FLO) was observed (its direct effect was significantly positive, but the indirect effect was not significant). The reason could be that Shaanxi has not formed the interaction effect of resource circulation due to the segmentation barriers of its geographic conditions. However, the construction of local highways and the enhancement of transport capacity can ensure the improvement of the four capacities of WEF-Nexus system resilience security.

The three effects of DEN and URB were significantly positive, indicating that promoting population agglomeration and industrial agglomeration, strengthening the functions of towns and cities, clarifying the division of labor between urban and rural areas, and reinforcing the free flow of population and resource factors are important ways to enhance the WEF-Nexus system resilience security in Shaanxi.

6. Discussion and Suggestions

The results of this study indicated that significant differences are present, which influenced the degree and direction of the direct, indirect, and total effects of the external driving factors of WEF-Nexus system resilience security across the whole study area. Additionally, there is significant regional variability across different regions. The main issues hindering WEF-Nexus system resilience security in the study scope include the following: the level of marketization of resource allocation is uneven, and the formulation and implementation of relevant government policies are not sufficiently precise and effective to form a good match with market mechanisms. Some areas cannot form an efficient resource circulation network because of the disadvantages of their natural transport conditions. The large population base puts greater pressure on the supply side of the WEF-Nexus system, and there is an inconsistency between the direction of population concentration and resource industry concentration, which fails to fully exhibit the four capacities of the WEF-Nexus system resilience security. The rate of return on the TEC and the ENV is relatively low.

To address the above issues, we propose four suggestions to improve the regional WEF-Nexus system resilience security.

First, there is a need to coordinate the planning of the whole situation and establish a system for circulating regional resource elements to ensure that the elements of the WEF-Nexus system can flow freely and efficiently in all circumstances. The aggregation of resource factors and the population is isotropic, and obstacles to interregional population mobility indirectly hinder the rational aggregation of resource factors; therefore, regional population policies need to be formulated according to the law of resource mobility under the market mechanism. Specifically, it is necessary to incorporate the management of the floating population into the overall planning of regional strategic development, weaken the household registration system, reduce the difficulty of settling down for the employment of the floating population, guarantee the basic social welfare of the floating population, establish a complete labor force employment system, and guide the diversion of the labor force to supplement the resource sector where the WEF-Nexus system has a labor shortage.

Second, transport conditions are important for the circulation of interregional resource factors, and increasing the transport capacity can increase the source power of regional development, increase the convenience and total volume of exchanges of resource factors between regions, and thus, guarantee the spatial connectivity of the elements of the WEF-Nexus system. Specifically, it is necessary to coordinate the overall transport structure of the basin, promote modernization and informatization management of the transport industry, optimize the division of labor between river navigation and road transport in the basin, and rationally plan the construction of transport infrastructure based on the geographic conditions of different regions to promote the overall scale of the resource circulation network in the basin.

Third, an integrated resource market system needs to be constructed in the basin, and a mechanism needs to be developed to integrate and allocate regional resources. If the transport capacity is considered the carrier of the spatial flow of resource elements, then the market mechanism serves as its potential carrier. The integration of the resource market can break the monopoly of the resource industry in each administrative region and the isolation of the resource market, then solve the problem of insufficient effective supply of resource categories in a single region and maximize the value of resources. Each administrative region needs to increase its sense of openness, create a regional resource trading platform, and form a cross-regional trading system for the resource industry sector, the banking sector, and the financial sector.

Fourth, the role of the core city needs to be strengthened as a radiation driver for neighboring cities. The core city usually becomes the priority supply of various types of regional resources. Thus, the core city with the good performance of the WEF-Nexus system resilience security is also responsible for driving the surrounding cities. When the core region is provided with sufficient resource production factors to make the resource sector prosperous, it should avoid the self-improvement qualities of the exhaustible resource sector, led by the energy sector, and utilize the characteristics of higher resource returns and less difficulty in transferring human capital between the resource industry and the manufacturing industry to promote the accumulation of related high-tech industries and human capital in the core region, thus providing convenient conditions for related technological innovation. Technological advancements will continuously improve the capacity for intensive and economical use of resources, achieve a shared and symbiotic relationship with water, energy, and food in the peripheral areas, and counter-complement the industries related to the WEF-Nexus system in the peripheral areas, thus forming a pattern of industrial linkage in which the modernization of the resource sector and high-tech industries in the core areas are coordinated with the gradients of agriculture, manufacturing, and ecology under the resource sector in the peripheral areas. Eventually, a core-driven peripheral WEF-Nexus system resilience security space spillover effect is formed.

7. Shortcomings and Outlooks

First, due to the workload, personal scientific research capacity, and challenges in data acquisition, only 40 cities out of the 73 cities in the Yellow River Basin were selected as samples for this study. This limitation is expected to be addressed in future research that will expand to cover the entire Yellow River Basin. Furthermore, the policies proposed for WEF-Nexus resilience security in the study area are more focused on the macro level and lack specificity. However, they can still provide valuable references for decision-makers regarding the direction of strategic policy formulation for WEF-Nexus system resilience security, given the limited existing research on the topic.

Second, the research approach in this study treats WEF-Nexus resilience security as a comprehensive index to be evaluated and seeks to explore the external driving factors. However, it does not aim to detail the complex relationships within the system.

Third, the model of the external driving factors of WEF-Nexus resilience security constructed in this study has low explanatory power because of the excessive difficulty in quantifying the variables related to environmental factors. It is hoped that with technological advancement and disciplinary development, a relatively standard and widely applied quantification system for factors such as climate and environmental quality can emerge to further optimize the model and fully explore the driving mechanism of environmental factors affecting WEF-Nexus resilience security.

Fourth, during the research period of this study, the COVID-19 pandemic emerged globally between 2021 and 2022. It was observed that there were significant fluctuations in the data of certain indicators during the empirical analysis, which may have had an impact on the results. However, due to time and workload constraints, these fluctuations could not be empirically verified. It is hoped that future studies will address this issue.

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