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Original Research

Research on the Coordination of Ecosystem Services and Matching of Water and Land Resources Taking the Huaihe River Basin as an Example

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Abstract

Investigating the correlation between ecosystem services and the alignment of water and land resources facilitates the sustainable development of ecological resources. The Huaihe River Basin was selected as the research subject, employing the equivalent factor approach to quantify the ecosystem service value (ESV) and assess the matching coefficient of water and land resources. The coupled coordination degree model was employed to investigate the synergistic development trend between the two entities. The Dagum Gini coefficient was employed to analyze the origins of regional variation in coordination degree. The results show that: (1) The ESV has risen by 12.294 billion yuan. The average ESV of the land is elevated in the east and diminished in the west. (2) The matching coefficient of water and land resources exhibits an increasing tendency. The transformation from 2010 to 2020 is more favorable in the interior compared to the periphery and more advantageous in the north than in the south. (3) The degree of coupling coordination exhibits a declining trend and a distribution pattern characterized by "higher in the east and lower in the west". The disparity in the level of coupling coordination among regions is progressively widening. The contribution rate of inter-regional disparities is 75.36%.

Keywords: ecosystem service value, water and land resources matching coefficient, harmonization, Huaihe River Basin

Introduction

Ecosystem services refer to the diverse advantages that humans can obtain from ecosystems. The value of ecosystem services (ESV) refers to the monetization employed to assess the functionality of the services rendered and the worth of the products generated by ecosystems [1]. Water land encompasses the natural environment, land, and water resources. It is crucial for establishing a novel framework for territorial spatial development and conservation, serving as a flood

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mitigation barrier and an ecological landscape corridor. A responsive correlation exists between watershed ecosystem services and water and land resources. Water and land resources serve as catalysts that affect alterations in ecosystem services. Examining the dynamics of ESV can aid managers in implementing modifications to the water and land resource environment. In recent years, the rapid industrialization and urbanization in China have resulted in substantial alterations in land use, inefficient water resource utilization, and severe water and land pollution issues. Substantial alterations have influenced the trade-offs within water land ecosystems and the interplay of water and land resource systems. A comprehensive examination of the interdependent interaction between ESV and water and land resources within the water land facilitates the sustainable utilization of ecological resources.

Presently, research on the extent of coordination between ESV and water and land resources in water land encompasses three primary facets. The initial focus is a study of a singular facet of ESV: water and land resources. Xie G.D. et al. introduced a revised ESV equivalent factorization table informed by their expertise in China's ecological domain [2]. It has been extensively utilized to evaluate ESV across multiple scales, including national [3], water land [4], urban agglomeration [5], provincial [6], and urban levels [7]. At the water land level, researchers have examined the various types of ecosystem service functions, value assessments, trade-offs, and synergistic impacts from multiple perspectives, including land use types, spatial and temporal scales, and geographical dimensions [8, 9]. Jin Y. et al. employed the Markov-PLUS model to simulate the land use patterns and ecosystem service value of the Shiyang River Basin in 2030, facilitating the calculation of ecosystem service value for arid inland rivers under various scenarios [10]. Scholars primarily examine the carrying capacity, utilization efficiency, shortage risk, and rebound effect of water resources alongside the carrying capacity of land resources, the implications of spatial mismatch, and alterations in utilization types [11-14]. He G. et al. employed the TOPSIS model to assess and analyze the water resource-carrying capacity of Anhui Province. Utilizing Geodetector, they investigated the determinants of the spatial and temporal variability of water resource carrying capacity [15]. Sun F. et al. employed the mediated effect concept alongside the control function method. The researchers examined the influence of urban administrative levels on land use efficiency and the mechanisms involved, employing both theoretical and empirical data [16]. The second field of study investigates the relationship between water and land resources and ESV. For water resource systems, scholars usually conduct research based on the wholeness of regional ecosystems. They incorporate ecosystem services into the development, carrying capacity, sustainable development, and multidimensional equitable distribution of water resources, upon which they establish a logical framework and theoretical model for water resources research [17, 18]. Wang F. et al. introduced "partition classification" as a precise control strategy grounded in the relationship between ecosystem service function and water quality to enhance the differentiated management of aquatic ecosystems [19]. Researchers have employed models such as FLUE-S [20], CA-Markov [21], and FLUS [22] to accurately delineate and simulate land-use categories for land resources, thereby investigating regional ecosystems for variations in structure, function, and value. Chen M. et al. utilized ArcGIS software to investigate the land use structure and spatio-temporal transition patterns in the Huaihe River Basin [23]. The third pertains to analyzing the alignment of water and land resources. Researchers predominantly assess this type of study utilizing a matching degree model and the Gini coefficient. Li X. et al. employed the agricultural water and land resources equivalent coefficient to assess the deficiency of water and land resources in Shandong Province [24]. Liu Y. et al. developed an analytical model for aligning agricultural water and land resources. They examined the quantitative ratio between accessible water resources for agricultural output and arable land resources suited for spatial and temporal alignment in Northeast China [25].

At present, researchers have attained a substantial body of findings. The majority of current research concentrates on singular systems (ecosystems, water resource systems, or land resource systems) and dual systems (water resources and ecosystems, land resources and ecosystems, and water resources and land resources systems). Contemporary researchers have produced substantial findings, mostly concentrating on singular systems (ecosystem or water resource system) and dual systems (water resources and ecosystem, land resources and ecosystems, water resources and land resource system).

The absence of accurate measurement of the correlation between watershed ecosystem services and water and land resources hinders the attainment of sustainable ecosystem service provision and the optimal distribution of water and land resources concurrently. Consequently, we assessed the matching coefficients of ESV and water and land resources for each city in the Huaihe River Basin utilizing the equivalent factor approach and the water and land resources matching coefficient. Subsequently, we examined the attributes of their spatial and temporal evolution patterns. Then, we employed the coupled coordination degree model to examine the synergy between the two entities. On this basis, we use the Dagum Gini coefficient to examine the fundamental reasons for regional spatial disparities and provide actionable recommendations for the sustainable ecological development of the Huaihe River Basin.

Materials and Methods

Overview of the Study Area

The Huaihe River Basin (N30°55′~36°36′, E111°55′~121°25′) is the sixth largest basin in China. The whole area is around 270,000 km^2, and the overall length is roughly 1,250 km. It includes four provinces: Henan, Anhui, Jiangsu, and Shandong. The basin is located in the climatic transition zone between northern and southern China. The northern region is classified as a warm temperate semi-humid monsoon climatic zone, whereas the southern region is categorized as a subtropical humid monsoon climate zone. Cultivated land comprises approximately 80.1% of the total category. The southern and western regions mostly consist of woodland and grassland, with grassland comprising approximately 8.2% and forest land about 2.1%. The distribution of construction land is uniform, accounting for around 6.3%. The water land is predominantly concentrated in the country's eastern region, with less than 2.5% of the area remaining unused (Fig. 1).

Research Methodology and Data Sources

Methodology for ESV Measurement

The equivalent factor technique, as proposed by Xie G.D. et al., was employed to assess the ESV in the Huaihe River Basin. The economic value of a unit of ecosystem service value equivalent factor is, on average, one-seventh of the market value of the national average grain yield for that year. The formula is:

$$e = \frac{1}{7}\sum_{c=1}(p_c q_c s_c) \Big/ \sum_{c=1} s_c \quad (1)$$

Where e denotes the economic value per unit of ecosystem service value equivalent factor (yuan/hm^2), c denotes the category of food crops, specifically rice, corn, wheat, and soybeans. P_c denotes the market pricing for food crops in category c (yuan/kg), q_c denotes the yields for food crops in category c (kg/hm^2), and s_c denotes the area cultivated for food crops in category c (hm^2). Further, the value coefficients of ecosystem services per unit area were calculated. The formula is:

$$V_{VCjk} = eq_{jk} \quad (2)$$

Where V_{vcjk} denotes the value coefficient per unit area of ecosystem service j provided by site type k (yuan/hm^2), q_{jk} denotes the dimensionless equivalent factor of the j ecosystem service provided by site type k.

The ecosystem service value for each city in the Huaihe River Basin was then computed. The formula is:

$$E_{ESVi} = \sum_{j=1}^{m} E_{ESVij} = \sum_{j=1}^{m}\sum_{k=1}^{n} A_{ik} V_{VCjk} \quad (3)$$

Where E_{ESVi} denotes the aggregate value of ecosystem services in city i within the Huaihe River Basin (yuan), E_{ESVij} denotes the value of ecosystem service j in city i of the Huaihe River Basin ecosystem (yuan), A_{ik} denotes the area of site type k in city i (hm^2).

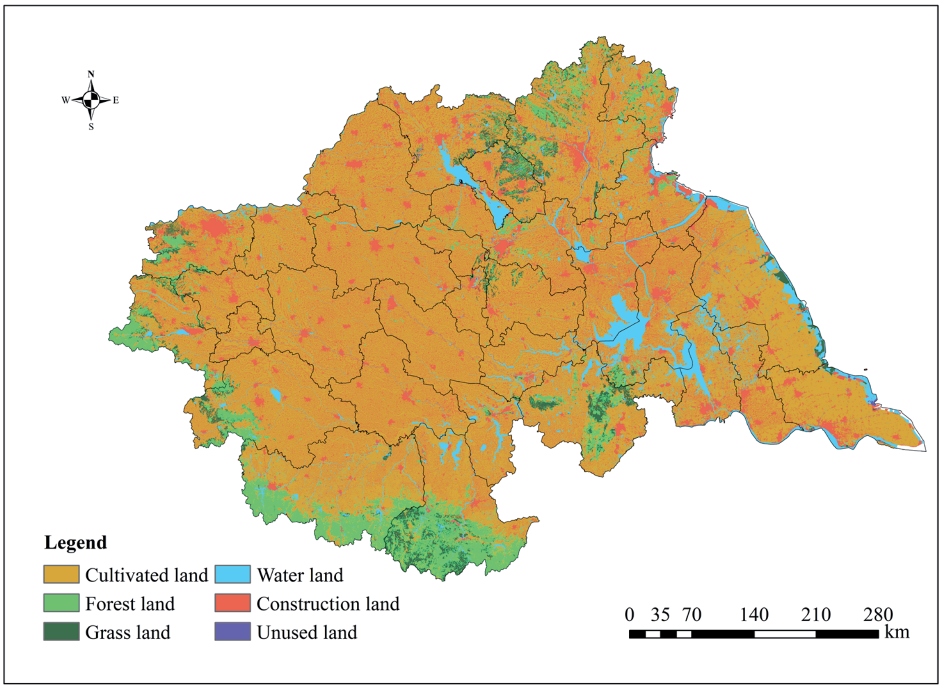

Fig. 1. Land use distribution map of Huaihe River Basin.

Methodology for Measuring the Matching Coefficient of Water and Land Resources

We employed the matching coefficient to assess the compatibility of water and land resources in the Huaihe River Basin. It can disclose the equilibrium condition and level of contentment about the geographical and temporal allocation of water and land resources in urban areas of the Huaihe River Basin. The formula is:

$$R_i = W_i \delta_i / S_i \tag{4}$$

Where R_i denotes the water and land resource matching factor for city i (10^4 m^3/hm^2), W^i denotes the volume of water accessible in city i (10^8 m^3), δ_i denotes the proportion of agricultural water in total water use in city i(%), Si denotes the quantity of arable land resources in municipality i (10^4 hm^2).

Methodology for Measuring Coupling Coordination

Coupling refers to the interaction and influence between two or more systems. The degree of coupling assesses the strength of the relationship between distinct systems; a higher degree of coupling indicates a stronger association between the systems. A complicated interrelationship occurs among nature, economy, and society. A modification or advancement in one of these systems will influence the other systems, consequently affecting the stability and progression of the overall system. In linked systems, interactions may be bidirectional or multidirectional. They induce alterations in one another's states, behaviors, or attributes via physical connections or interactions. This interaction establishes a correlation among the systems, leading to the entire system demonstrating integrity and synergy. As the economy and society undergo high-quality development, assessing a region's or society's development level transcends a singular focus, emphasizing a comprehensive evaluation of balanced development grounded in coordination and advancement levels. The reciprocal relationship between the value of ecosystem services and the alignment of water and soil resources entails intricate linkages across economic, social, and ecological systems. The congruence of water and land resources directly influences the ecosystem's health, thus impacting its service functions and value. The sufficiency and consistency of water resources influence plant growth, influencing the ecosystem's primary productivity and provisioning functions. Soil fertility and structure influence vegetation cover and biodiversity, significantly affecting the ecosystem's regulating functions. Overutilization or contamination of water resources and the deterioration of land resources can undermine water supply services and land production, diminishing the long-term functional capacity of ecosystems. Ecosystems affect water and land resources' spatial distribution and compatibility via regulatory and supportive functions. The degradation of ecosystem services diminishes the protective and regulatory roles of water and land resources, potentially intensifying the disparity between these resources. Consequently, the correlation between ecosystem service value and the alignment of water and land resources is complementary. A comprehensive analysis of the relationship between the two facilitates the harmonious combination of rational resource development and ecological conservation.

The coupling degree model is employed to assess the coordination between ESV and the alignment of water and land resources in the Huaihe River Basin, with the calculation formula being:

$$C = \left[2E_{ESV} R / (E_{ESV} + R)^2 \right]^{1/2} \tag{5}$$

In the formula, C denotes the degree of coupling between the ecosystem service value and the water and land resource compatibility in the Huaihe River Basin. E_{ESV} and R denote the standardized land-averaged ecosystem service value and water and land resource matching coefficient, respectively.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{6}$$

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{7}$$

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{8}$$

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{9}$$

The normalization process for the max-min indicator involves designating the original matrix as $X = (x_{ij})_{m\times n}$, as seen in formula (6), where m denotes the number of cities, n signifies the number of indicators, and x_{ij} represents the original data for the i city and j indicator. Normalization of positive and negative indicators is executed using formulas (7) and (8), respectively, resulting in the standardized matrix $Y = (y_{ij})_{m\times n}$, as delineated in formula (9).

$$D = \sqrt{CT} \tag{10}$$

$$T = aE_{ESV} + bR \tag{11}$$

Where D denotes the degree of coupling and coordination between the ESV and the corresponding status of water and land resources, it assumes a value from 0 to 1. The greater the value, the more likely the two are to synchronize their development.

Table 1. Criteria for grading the degree of coupling coordination.

Developmental stage	Typology	Degree of coupling coordination
Uncoordinated development	Extreme disorder	$0 \leq D < 0.1$
	Severe disorder	$0.1 \leq D < 0.2$
	Moderate disorder	$0.2 < D \leq 0.3$
	Mild disorder	$0.3 < D \leq 0.4$
Transition period	Near disorder	$0.4 < D \leq 0.5$
	Basic coordination	$0.5 < D \leq 0.6$
Coordinated development	Primary coordination	$0.6 < D \leq 0.7$
	Intermediate coordination	$0.7 < D \leq 0.8$
	Good coordination	$0.8 < D \leq 0.9$
	Quality coordination	$0.9 < D \leq 1$

T denotes the level of comprehensive evaluation of the ESV and the compatibility status of water and land resources in the Huaihe River Basin. A and b denote weighting factors. For the comprehensive, coordinated advancement of the system, enhancing the capacity for ecosystem service supply is as crucial as the sustainable management of water and land resources. Consequently, both assume the value of 0.5. According to the current research findings [26], the coupling coordination degree is categorized into three developmental stages and ten forms of coordination, as illustrated in Table 1.

Dagum Gini Coefficient Method

The Dagum Gini coefficient approach is a decomposition technique introduced by Dagum. This can effectively resolve the issue of overlapping samples. Generally, based on the calculation of the overall Gini coefficient G of all subgroups, the spatial difference Gini coefficient G is deconstructed into three parts: the contribution of intra-regional geographical disparities Gw, the contribution of inter-regional spatial disparities Gnb, and the contribution of inter-group (super-variable density) disparities Gt. These three fulfill the equation G = Gw + Gnb + Gt. Consult Zhao W. and other scholars for particular calculating formulas [27].

Data Sources

Land use statistics for cities in the Huaihe River Basin for 2010, 2015, and 2020 were sourced from the Resource and Environment Science and Statistics Centre of the Chinese Academy of Sciences (http://www.resdc.cn). The spatial resolution is 30 m by 30 m. Based on the national standard GB/T1010-2017 Classification of Land Use Status [28] and considering the actual conditions of the study region, we classified land use types into six categories: cultivated land, forest land, grassland, water land, construction land, and unused land. We assigned a value of zero to the ecosystem services provided by developed land [29]. In our ESV calculations, we utilize grain prices and production per unit area, and we determine the matching coefficient for water and land resources through variables such as water availability and agricultural water consumption. These originate from the Henan Statistical Yearbook, the Anhui Statistical Yearbook, the Jiangsu Statistical Yearbook, and the Shandong Statistical Yearbook.

Results and Discussion

Analysis of ESVs

An Analysis of Temporal and Spatial Evolution

Table 2 classifies the ESVs in the Huaihe River Basin according to land use categories. The ESV of the Huaihe River Basin experienced consistent growth from 2010 to 2020, culminating in an increase of 12.294 billion yuan, representing a growth rate of 1.76%. This signifies that the ESV of the Huaihe River Basin has enhanced overall. During the study period, water land constituted the predominant proportion of ESV in the Huaihe River Basin, exceeding 50% of the total ESV. The ESV of cultivated land is 23.02% on average over several years. The ESV hierarchy of several land categories in the Henan, Anhui, Jiangsu, and Shandong sections is as follows: water land > cultivated land > forest land > grassland > unused land. From 2010 to 2020, the ESV of water land increased by 16.107 billion yuan. The ESV of water land has risen in the Henan, Anhui, Jiangsu, and Shandong sections. The Jiangsu section exhibits the most significant growth of 4.22%. The primary explanation for this may be that the Huaihe River Basin was the first region in China to experience complete and integrated management in compliance with legal standards. In 2006, the "Water Special Project" designated the Huaihe River Basin as a principal demonstration basin. This has resulted in the collaborative advancement of scientific and technological innovation with engineering management, and the reintroduction of plows to lakes has proven effective. Between 2010 and 2020, the ESV of cultivated land and forest land in the Huaihe River Basin diminished by 3.287 billion yuan and 0.411 billion yuan, respectively. In Henan, Anhui, Jiangsu, and Shandong sections, the ESV of cultivated land and forested land diminished. The ESV for forest land in the Jiangsu section was markedly lower than in other provinces. The grassland ESV in the Huaihe River Basin initially declined and subsequently rose, resulting in a net drop of 0.096 billion yuan. Only the Jiangsu section showed a slight increase, while the Henan, Anhui, and Shandong sections demonstrated a declining trend. During the decade, cultivated land, forest land, grassland, and unused land exhibited various levels of decline in ESV. The rise in water land ESV alone offset the decline in ESV across other land categories. This ultimately contributed to the rise in total ESV in the Huaihe River Basin.

Evolution of Spatial Patterns and Identification of Problem Areas

Fig. 2 depicts land-averaged ESV's regional distribution and volatility in the Huaihe River Basin. The Huaihe River Basin displays a regional distribution of land-averaged ESV characterized by a gradient of "high in the east and low in the west". Cities exhibiting a land-averaged ESV exceeding 30,000 yuan/hm^2 are predominantly located in Jiangsu, including Suqian, Yancheng, Huai'an, and Yangzhou. The Anhui section's northern region and the Henan section's southern region predominantly comprise cities with land-averaged ESV below 10,000 yuan/hm^2, including Shangqiu, Zhoukou, Fuyang, and Bozhou. This results from substantial disparities in physical geographic conditions and land use patterns across various locations. Regarding changes in ESV in cities of the Huaihe River Basin, over 50% of the cities in the study area had an increase in land-averaged ESV, signifying the effectiveness of ecological development in the region. Land-averaged ESV rose in 18 cities, comprising Zhengzhou, Kaifeng, Pingdingshan, Xuchang, Shangqiu, and Zhoukou in Henan; Bozhou, Fuyang, Chuzhou, and Lu'an in Anhui; Lianyungang, Huai'an, Yancheng, and Suqian in Jiangsu; and Zaozhuang, Rizhao, Linyi, and Heze in Shandong. They all share that the water land areas have expanded to varying extents. The increases are chiefly attributable to extensive areas of cultivated land and grassland, with the unit value coefficients of water land significantly exceeding those of cultivated and unused land, leading to an elevation in ESV. Lianyungang

Table 2. Changes in the ESV of different land use categories in the Huaihe River Basin (Unit: 10^8 yuan).

Year	Area	Cultivated land	Forest land	Grassland	Water land	Construction land	Unused land	Total value
2010	Henan section	452.46	274.08	39.28	487.61	0.00	0.00	1253.66
	Anhui section	397.84	264.39	83.69	650.62	0.00	0.16	1396.70
	Jiangsu section	526.21	61.03	21.04	2729.06	0.00	0.07	3337.41
	Shandong section	256.75	85.87	64.51	576.93	0.00	0.05	984.11
	Huaihe River Basin	1633.26	685.37	208.52	4444.22	0.00	0.28	6971.65
2015	Henan section	446.45	274.00	39.24	499.83	0.00	0.00	1259.55
	Anhui section	392.27	263.94	83.27	681.69	0.00	0.18	1421.22
	Jiangsu section	520.80	60.34	20.16	2725.06	0.00	0.06	3326.41
	Shandong section	254.31	85.76	64.40	581.18	0.00	0.05	985.69
	Huaihe River Basin	1613.82	684.03	207.06	4487.64	0.00	0.29	6992.84
2020	Henan section	440.10	273.51	38.59	505.10	0.00	0.00	1257.33
	Anhui section	390.09	262.73	82.82	670.59	0.00	0.004	1406.24
	Jiangsu section	517.21	59.16	21.85	2844.34	0.00	0.02	3442.59
	Shandong section	252.99	85.87	64.30	585.26	0.00	0.05	988.46
	Huaihe River Basin	1600.39	681.26	207.56	4605.29	0.00	0.07	7094.59

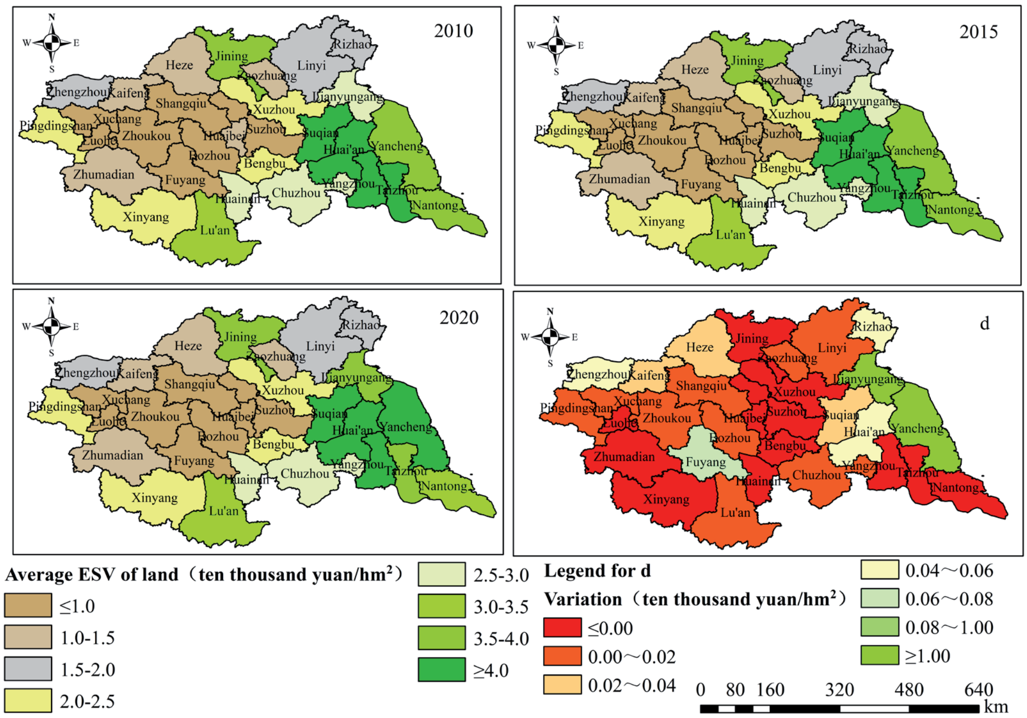

Fig. 2. Spatial distribution of land-averaged ESV and its changes in the Huaihe River Basin.

achieved the highest rise in land-averaged ESV, amounting to 8,700 yuan/hm^2, with a matching increase in the value of water land of 20,511.03 hm^2. On the one hand, between 2010 and 2016, Lianyungang experienced an average annual rainfall of 840.22 mm, resulting in a total transit volume of around 5.942 billion m^3. Lianyungang's continuous enhancement and restoration of current water conservancy initiatives has augmented its rainfall and flood retention capacity, enabling the city to optimize its utilization of rainfall and flood resources. On the other hand, Lianyungang, leveraging its strategic geographical position, has been diligently developing seawater desalination facilities to mitigate the issue of water scarcity. Twelve cities in Henan (Xuchang, Xinyang, Zhumadian), Anhui (Huaibei, Suzhou, Bengbu, Huainan), Jiangsu (Xuzhou, Nantong, Yangzhou, Taizhou), and Shandong (Jining) exhibit an ESV change of less than zero. Development land has expanded in all these cities, degrading its fundamental ecological service function. The primary cause for the reduction in their ESV is the transformation of distinct land classifications into construction land. Between 2010 and 2020, the alterations in the water land of the six cities – Xinyang, Suzhou, Huainan, Xuzhou, Nantong, and Jining – were -1275.28, -16.56, -213.52, -184.63, -10535.59, and -574.01 hm^2, respectively. The variation in the construction land area is 9506.88, 10439.73, 7739.10, 18162.39, 34203.45, and 14874.76 hm^2. This signifies that the urbanization process in these places has been highly successful, and the extent of expansion has been considerable; nonetheless, the ecological environment has suffered degradation, necessitating enhanced environmental protection measures. The five cities of Xuchang, Zhumadian, Huaibei, Bengbu, Yangzhou, and Taizhou have expanded their water and construction land areas; however, their cultivated, forest, and grassland areas have diminished to varying extents, leading to a continued decline in per capita ESV.

Analysis of the Matching Coefficient of Water and Land Resources

Fig. 3 depicts the spatial distribution and variations in the matching coefficient of water and land resources within the Huaihe River Basin. We classified the compatibility of water and land resources into five categories: extremely poorly matched (0-0.22), poorly matched (0.22-0.44), average matched (0.44-0.66), good matched (0.66-0.88), and better matched (0.88-1.10).

The spatial distribution pattern of water and land resource matching status in 2010, 2015, and 2020 is notably similar, demonstrating a pattern of high concentration in the east and low concentration in the west. The regions with poorly matched water and land resources are contiguously distributed in the western portion of the Huaihe River Basin, including three cities in the northeastern segment of Shandong.

From 2010-2020, a significant disparity exists in the match rating of water and land resources across various locations. In Yangzhou, the compatibility between water and land resources diminished from excellent to good. Huai'an experiences through "good → poor → average". In Kaifeng, Fuyang, and Chuzhou,

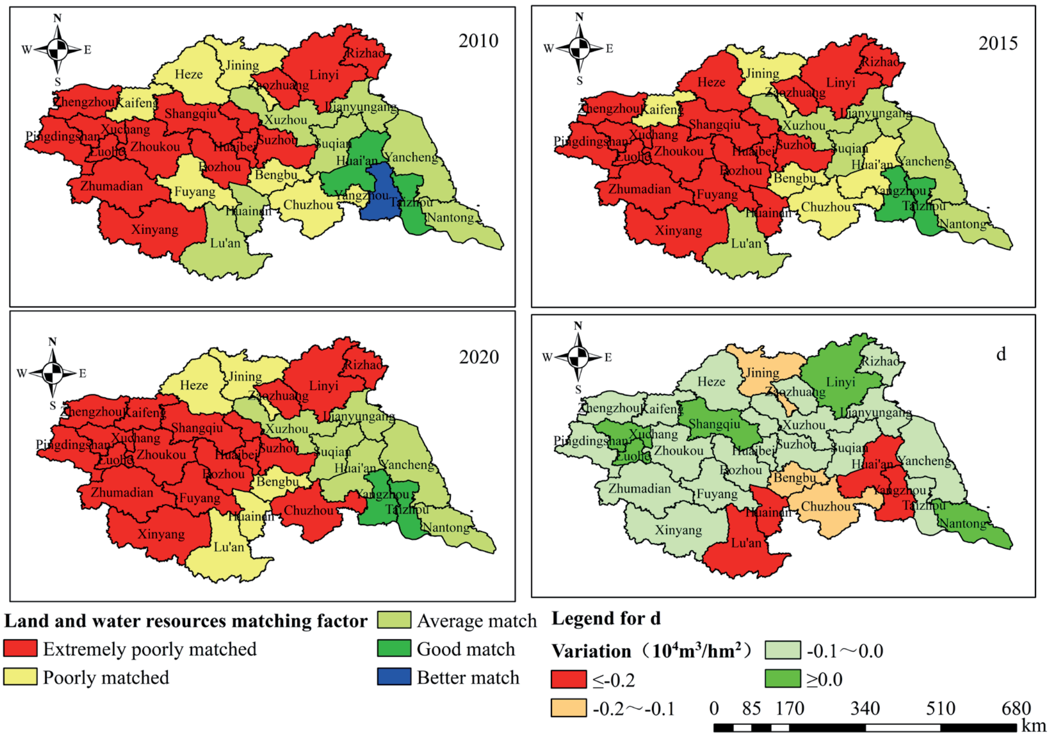

Fig. 3. Spatial distribution of the coordination matching coefficient of water and land resources and its changes in the Huaihe River Basin.

the compatibility of water and land resources declines from inadequate to severely inadequate. During the study period, the average matching coefficient of water and land resources for each province is as follows: Jiangsu (0.60) > Anhui (0.24) > Shandong (0.20) > Henan (0.13). Simultaneously, significant disparities between cities exist in the matching coefficients of water and land resources. In 2010, Yangzhou exhibited the highest water and land resource match factor of 1.07, while Zhumadian recorded the lowest match value of 0.05 in 2020.

The alteration in the matching coefficient of water and land resources in the Huaihe River Basin exhibits the characteristic that "the interior is superior to the periphery, and the northern region is superior to the southern region". The most pronounced decline in the matching coefficient of water and land resources occurred in the cities of Huainan, Lu'an, Yangzhou, and Huai'an, with alterations of 0.30, 0.27, 0.26, and 0.21 ten thousand m^3/hm^2, respectively. Only the coefficients for water and land resources in Xuchang, Luohe, Shangqiu, Linyi, and Nantong exhibited an increase beyond 0, signifying a favorable development trend, while the remaining municipalities had a slight loss.

Coupling Coordination Analysis of ESV and Matching Coefficient of Water and Land Resources

Fig. 4 depicts the coupled coordination degree of ESV and the matching coefficients of water and land resources in the Huaihe River Basin. Throughout the study period in the Huaihe River Basin, the average coupling coordination between the ESV and the matching coefficient of water and land resources initially declined and subsequently rose. In 2010, 2015, and 2020, the coupling coordination degree of the Huaihe River Basin was recorded at 0.5477, 0.5087, and 0.5115, respectively. All aspects are characterized by barely any coordination and are in a transitional phase from uncoordinated to coordinated development. The coupling coordination between the Henan and Shandong sections has diminished, with the Henan section's coordination declining from mild disorder (0.3239) to moderate disorder (0.2911). The coordination level of the Shandong section diminishes from basic coordination (0.5208) to near disorder (0.4680). The level of coupling coordination in both the Anhui and Jiangsu sections initially declines and subsequently rises. The coupling coordination level in the Anhui section is "basic coordinated (0.5355) → near disorder (0.4716) → near disorder (0.4882)". The coupling coordination level in the Jiangsu section transitions from "good coordination (0.8284) → intermediate coordination (0.7972) → good coordination (0.8101)". Specifically, Lianyungang's coupling degree of coordination increased most markedly by 0.06. This illustrates Lianyungang City's commendable accomplishments in executing ecological and environmental management initiatives and addressing national green development throughout the 13th Five-Year Plan era. Chuzhou has the most significant reduction in coupling coordination, measuring 0.16, mostly due to the decline in the water and land coordination matching coefficient from 0.40 to 0.22. In recent years, Chuzhou has excessively

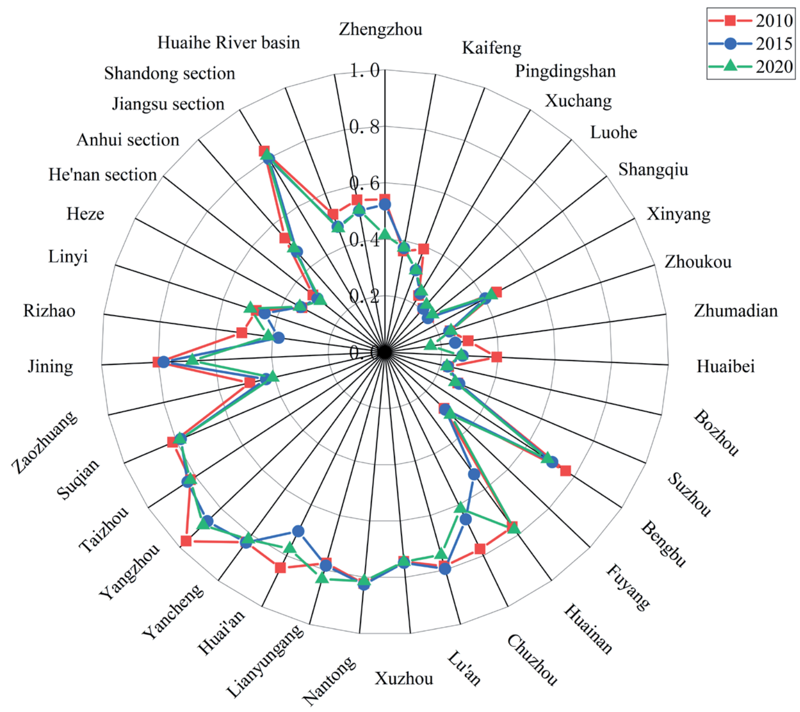

Fig. 4. Coupled coordination of ESV and water and land resources matching coefficient in the Huaihe River Basin.

developed and utilized water and land resources, leading to land erosion in arable land that constitutes 27.08% of the total arable land erosion in Anhui Province. To avert further decline in its coupling and coordination, Chuzhou's future development must aim to foster the simultaneous advancement of urban growth and ecological preservation, prioritizing environmental conservation.

Fig. 5 illustrates the spatial distribution and alterations of the coupling coordination types between ESV and the water and land resource matching coefficient in the Huaihe River Basin. Throughout the study period, the average coupling coordination degree of ESV and the water and land resource matching coefficient in the Huaihe River Basin was as follows: Jiangsu section (0.8119) > Anhui section (0.4984) > Shandong section (0.4878) > Henan section (0.3064), indicating a spatial pattern of "higher in the east, lower in the west". This aligns with the spatial distribution pattern of ESV and the matching coefficient of water and land resources. Cities in the eastern region of the Huaihe River Basin typically demonstrate elevated levels of coupling coordination, including quality coordination and good coordination, whereas cities in the western region generally display diminished levels of coupling coordination, characterized by moderate and mild disorder. The primary rationale is that between 2010 and 2020, the GDP growth rates of the eastern cities – Nantong, Taizhou, Yangzhou, Yancheng, Lianyungang, and Huaian – were 189.59%, 159.32%, 225.81%, 155.21%, 174.62%, and 258.85%, respectively. The GDP growth rates for the western cities are as follows: Pingdingshan 87.35%, Xuchang 162.00%, Zhumadian 171.35%, Zhoukou 165.99%, and Xinyang 156.97%. This suggests that the economic development of eastern cities surpasses that of western ones.

Economic development can facilitate the market-oriented transformation of scientific and technological innovations and enhance resource use. Between 2010 and 2020, the energy consumption per ten thousand yuan of GDP in Nantong, an eastern region, declined from 0.664 to 0.347 tons of standard coal, whereas in Taizhou, it reduced from 0.206 to 0.174 tons of standard coal. In the western region, the energy consumption per 10,000 yuan of GDP in Shangqiu, Xuchang, and Zhumadian has declined from 0.898, 0.734, and 0.793 tons of standard coal to 0.577, 0.407, and 0.444 tons of standard coal, respectively. This signifies that, despite a substantial reduction in energy consumption per ten thousand yuan of GDP in the western portion of the Huaihe River Basin, the efficiency of resource usage remains inferior to that of eastern cities. The western section of the Huaihe River Basin, primarily in Henan, serves as a significant grain-producing hub in our nation. From 2010 to 2020, the average fertilizer consumption in Zhoukou, Zhumadian, Shangqiu, Xinyang, and Pingdingshan was 699,900, 708,400, 699,900, 462,500, and 344,000 tons, respectively. The mean fertilizer consumption in Taizhou, Nantong, Lianyungang, Huai'an, and Yangzhou is 169.6, 224.4, 325.6, 351.4, and 185.5 thousand tons, respectively. Agricultural fertilizers infiltrate the soil and aquatic systems, impacting ecosystem services' value. In 2020, the urbanization rates of cities

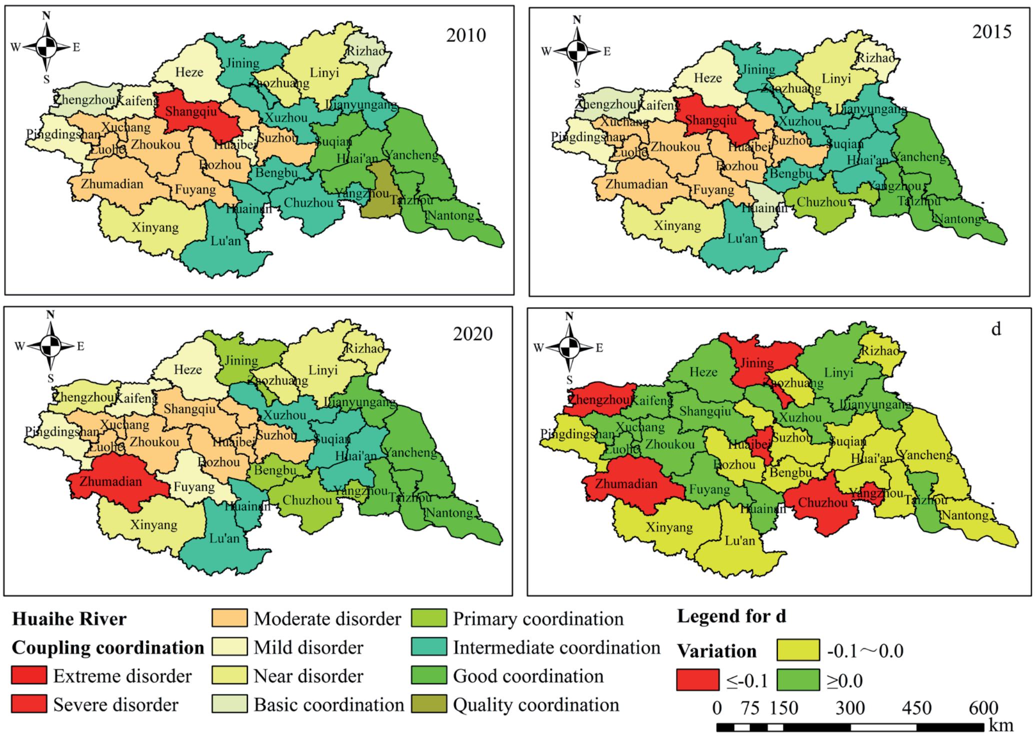

Fig. 5. Spatial distribution of coupling coordination between ESV and water and land resources matching coefficients and their variation in the Huaihe River Basin.

in the eastern Huaihe River Basin, including Yancheng, Nantong, Taizhou, Huai'an, and Lianyungang, exceeded 60%. In contrast, the urbanization rates of cities such as Pingdingshan, Xuchang, Luohe, Zhoukou, and Zhumadian ranged from 40% to 55%, significantly lower than those of the eastern cities. The green coverage rates in the built-up areas of Yancheng, Nantong, Taizhou, Huai'an, and Lianyungang are 43.6%, 43.6%, 42.6%, 42.6%, 45.0%, and 42.3%, respectively. The green coverage rates in the built-up regions of Pingdingshan, Xuchang, Luohe, Zhoukou, Zhumadian, and Zhengzhou are 41.60%, 41.60%, 39.90%, 45.50%, and 41.50%, respectively. Urban green spaces, parks, and other ecological infrastructures can boost air quality, mitigate soil compaction, and improve ecosystems' supply, support, control, and cultural functions. From the standpoint of the variation in coupling coordination degree, the coupling coordination degree between ESV and the water and land resource matching coefficient in the Huaihe River Basin predominantly exhibits a spatial distribution characterized by "negative in the east and positive in the west". The coupling coordination degree of Zhengzhou, Jining, Huaibei, Zhumadian, and Chuzhou has markedly declined. From 2010 to 2020, the mismatch in Zhumadian deteriorated from moderate to severe, with a 37.50% reduction in its water and land resource matching coefficient. Zhumadian is predominantly agricultural, with grain output continuously placing second in Henan Province; it faces significant challenges such as seasonal drought and soil erosion. These cities must remain attentive to the interdependent relationship between their ESV and water and land resources, implementing strategies to enhance the mutual relationship between ecological conservation and the development and utilization of these resources, thereby mitigating the risk of further degradation.

Regional Differences and Sources of Coupled Coordination

We intend to conduct a more in-depth examination of the origins of spatial differentiation in the coupling coordination degree of ESV, the compatibility coefficient between water and land resources in the Huaihe River Basin, and its evolutionary characteristics. The Huaihe River basin was segmented into sections corresponding to the provinces of Henan, Anhui, Jiangsu, and Shandong. The Dagum Gini coefficient was employed to compute the overall Gini coefficient, intra-area variance, inter-area variance, and hypervariance density of the coupling coordination degree, as illustrated in Table 3.

(1) Throughout the study period, the overall Gini coefficient reflecting the coupling coordination between ESV and the matching coefficients of water and land resources in the Huaihe River Basin exhibited an increasing trend. The value rose from 0.253 in 2010 to 0.264 in 2020, reflecting a growth rate of 4.35%. This signifies that the gap in the coupling coordination level of ecosystem service value and the matching coefficients of water and land resources among the 30 cities in the Huaihe River Basin is persistently

increasing. This may be attributed to substantial disparities in economic development, technological innovation, and resource endowments across various regions, which influence the overall disparity in the coupling coordination degree between ESV and the water and land resource matching coefficient.

Inter-regional disparities are the primary factor contributing to total inequalities. The Gini coefficient for inter-regional disparities rose from 0.187 in 2010 to 0.206 in 2020. The trend of inter-regional disparities aligns with overall disparities, suggesting a close relationship between the two. Regional disparities are gradually declining, with a reduction of 8.57%. This signifies that the gap in the coupling coordination degree between ecosystem service value and the matching coefficients of water and land resources across various places is progressively diminishing. The super-variable density observed during the period displays an "upward-downward" characteristic, suggesting that the crossover phenomenon between regions has a minimal effect on the overall Gini coefficient disparity of the coupling coordination degree between ESV and the matching coefficients of water and land resources in the Huaihe River Basin. The inter-regional contribution rate of the coupling coordination degree between ecosystem service value and the matching coefficient of water and land resources in the Huaihe River Basin has consistently stabilized between 70% and 80%, significantly surpassing intra-regional and super-variable density. The contribution rate of intra-regional disparities has diminished from 13.77% to 12.15%, underscoring the escalating polarization among various areas. The super-variable density has diminished from 12.37% to 10.03%, signifying a decrease in the extent of overlap in the evolution of regional coordination. In conclusion, inter-regional disparities are the primary cause of the coordination variances in the Huaihe River Basin. The regional coordinated development effect has not been properly achieved, and the geographical coordination and connection mechanism across provinces needs enhancement.

(2) Based on the differences within the region. The annual average values of regional disparities throughout the four provinces of the Huaihe River Basin are rated as follows: the Anhui section (0.245) surpasses the Henan section (0.182), which exceeds the Shandong section (0.147), followed by the Jiangsu section (0.033). The degree of coordination in the Anhui section predominates regional differentiation. The Gini index in the Henan section has consistently declined by 11.40%, signifying a trend towards fewer inequities in urban coordination within that region. Furthermore, the general coordination level in the Henan section is deteriorating. The correlation between the two systems in the Henan section is diminishing and trending negatively. The Gini coefficient in the Anhui section exhibits an increasing trajectory, rising from 0.238 in 2010 to 0.249 in 2020. Simultaneously, the average coordination degree in the Anhui section has diminished relatively rapidly. Huaibei has transitioned from mild imbalance to moderate imbalance, whereas both Bengbu and Chuzhou have shifted from intermediate coordination to primary coordination. With the exception of Fuyang, which has progressed from moderate to mild imbalance, the coordination levels of the other three cities remain constant, while their specific values exhibit a downward trend. This indicates that a disparity exists in the degree of coordinated growth among cities in the Anhui section throughout the observation period, and this phenomenon is progressively worse. The Gini coefficient in the Jiangsu region has consistently declined and is markedly lower than that of other sections. This indicates that the urban coordination in the Jiangsu section is in a steady, high-level condition. The Gini coefficient of regional disparities in the Shandong section increased from 0.149 in 2010 to 0.161 in 2015 and then declined to 0.132 by 2020, exhibiting an "increase-decrease" pattern. Furthermore, the average reduction in coordination levels for the Shandong section from 2010 to 2015 and from 2015 to 2020 was 8.83% and 1.47%, respectively, signifying that the coordination development levels

Table 3. Spatial differences and sources of coupled ESV and water and land matching coefficients coordination across provinces in the Huaihe River Basin.

Year		2010	2015	2020
Overall Gini coefficient		0.253	0.261	0.264
Intra-regional variations	Henan section	0.193	0.182	0.171
	Anhui section	0.238	0.249	0.249
	Jiangsu section	0.038	0.034	0.027
	Shandong section	0.149	0.161	0.132
Sources of interregional disparities	Henan section - Anhui section	0.271	0.256	0.267
	Henan section - Jiangsu section	0.267	0.269	0.277
	Henan section - Shandong section	0.220	0.214	0.202
	Anhui section - Jiangsu section	0.167	0.187	0.180
	Anhui section - Shandong section	0.222	0.230	0.224
	Jiangsu section - Shandong section	0.137	0.148	0.145
Sources of spatial variation	Regional	0.035	0.034	0.032
	Interregional	0.187	0.195	0.206
	Hypervariable density	0.031	0.033	0.026
Contribution of spatial variation	Regional	13.766	13.085	12.148
	Interregional	73.868	74.393	77.822
	Hypervariable density	12.366	12.521	10.030

among cities in the Shandong section are increasingly uniform, with the disparity progressively diminishing.

(3) Based on regional differences. The overall evolution indicates that regional disparities are typically rising, signifying that regional distinctions are becoming more pronounced. The regional disparities between the Henan and Jiangsu sections are the most pronounced, exhibiting an annual average Gini value of 0.271. The Gini coefficient for the Jiangsu and Shandong sections is the lowest, with an annual average of 0.143. The inter-regional Gini coefficients for the Henan-Anhui and Henan-Shandong sections are comparatively elevated, with declines of 1.48% and 8.18%, respectively, throughout the observation period. This signifies that the discrepancy in urban coordination among the Henan, Anhui, and Shandong regions is diminishing, and the imbalance in regional growth is steadily enhancing. The inter-regional Gini coefficients for the Henan-Jiangsu, Anhui-Jiangsu, Anhui-Shandong, and Shandong-Jiangsu sections exhibit an upward trend, with growth rates of 3.75%, 7.78%, 0.91%, and 5.84%, respectively. The elevated coordination level in the Jiangsu sector compared to the other three provinces may contribute to substantial regional disparities, potentially resulting in a "Matthew effect" in regional growth. Consequently, initiatives must be undertaken to mitigate regional discrepancies and foster spatially equitable growth of the coupling coordination between ecosystem service value and water and land resource matching coefficients in the Huaihe River Basin.

Discussion

(1) Quantify and analyze the ESV in the Huaihe River Basin, together with its geographical and temporal variation characteristics. Understanding the total ecosystem service level of the region is beneficial. On the one hand, it is helpful to understand the region's overall ecosystem service level. On the other hand, it is helpful for ecological and environmental protection and optimal control of land space in the region. In this study, the overall ESV of the Huaihe River Basin showed an upward trend during the last 10 years. This study indicates that the overall ESV of the Huaihe River Basin has exhibited an increased trend over the past decade. This signifies an enhancement in the ecosystem health of the Huaihe River Basin, aligning with the findings of Qiao X. and other researchers who assessed the ESV of the Huaihe River Basin [30]. The State Council's "Water Special Project", initiated in 2006, expedited the comprehensive management of the Huaihe River Basin. The primary elements influencing the ESV of the Huaihe River basin are water bodies, arable land, and forested areas. This outcome is identical to that of Zhang X.Y. et al. [31], Fu Y. et al. [32], and others. From 2010 to 2015, the ESV of the Huaihe River basin rose from 697.165 billion yuan to 699.284 billion yuan. In this period, the Huaihe River Basin experienced a rise in cultivated land, forest land, grassland, water land, and construction land by 325,200, 15,500, 12,700, 20,900, and 348,500 hm^2, respectively. Furthermore, the vacant property was converted into several land use categories. From 2015 to 2020, the ESV of the Huaihe River Basin rose from 699.284 billion yuan to 709.459 billion yuan. In this timeframe, cultivated land, forest land, and unused land diminished by 160,500, 6,800, and 6,500 hm^2, respectively. The transformation of these regions into grassland, water land, and construction land sites led to an augmentation of 1,000, 33,500, and 144,900 hm^2, respectively. The value coefficient per unit water area significantly exceeds that of both unused and arable land, enhancing the river's storage function. In 2020, the water area in the Jiangsu section will reach 866,600 hm^2, considerably surpassing that of the other three provinces. This aligns with the regional distribution of the land-mean ESV in the Huaihe River Basin, characterized by "higher values in the east and lower values in the west". The area designated for construction has been increasing significantly each year, and such land use adversely affects the ecosystem. Consequently, it is imperative to rigorously limit the dimensions of the development site and enhance the land-use configuration.

(2) Between 2010 and 2020, the alignment of water and land resources in the Huaihe River Basin exhibited a spatial distribution characterized by "higher levels in the east and lower levels in the west". This aligns with He G. et al.'s conclusion that the coupling and coordination of water and land resource use efficiency is superior in the southeastern section of the Huaihe River basin [33]. During the study period, the matching coefficient of water and land coordination was as follows: Jiangsu section (0.5973) > Anhui section (0.2391) > Shandong section (0.1951) > Henan section (0.1272). On the one hand, the inherent limitation of resource-based water scarcity exists. Henan and Anhui, the central and western provinces of the Huaihe River Basin, possess significant agricultural land resources, yet they face a pronounced issue of water resource scarcity, with 10.48% of the nation's arable land receiving merely 1.19% of its water resources. On the other hand, it is a human-induced result of the artificially created water scarcity. Jiangsu exhibits advanced digital agriculture growth, and the degree of agricultural mechanization is consistently rising [34]. The conventional agricultural business model continues to prevail in the remaining three provinces, requiring modifications to promote agricultural modernization.

(3) Fig. 3d) and Fig. 4d) indicate that from 2010 to 2020, the majority of cities in the Huaihe River Basin witnessed a decline in the matching coefficient of water and land resources by less than 0, whereas 18 cities observed an increase in the ESV by more than zero. Furthermore, the increase rate of the matching coefficient of water and land resources lagged behind the ESV. In the Huaihe River Basin, the spatial distribution of the coupling coordination degree, ESV, and the matching coefficient of water and land resources exhibit a pattern of "high in the east and low in the west", whereas the

spatial pattern of the change in coordination degree is "negative in the east and positive in the west". In other words, the eastern segment of the Huaihe River Basin is experiencing coordinated development; nevertheless, the correlation between ESV and the compatibility coefficient of water and land resources is exhibiting a declining trend. Conversely, several cities in the Henan, Anhui, and Shandong sections, characterized by a diminished level of coordination, are experiencing uncoordinated development, evidenced by low ESV and suboptimal matching coefficients of water and land resources, yet are progressively nearing a transitional phase.

Alterations in ecosystem services are induced by water and land resources, which are essential for production and habitation within the basin. Promoting consistent and beneficial alterations in the matching coefficients of ESV and water and land resources will enhance coordination between the two and facilitate the sustainable development of the Huaihe River Basin's natural environment.

This study possesses the subsequent limitations: (1) The coupled coordination degree model can illustrate the synergy between the value of urban ecosystem services and the alignment of water and land resources at a specific moment; however, it is unclear how this model addresses the characteristics of changes between the two over successive time intervals. Future research could utilize extended and continuous time-series data to precisely identify alterations in the synergistic state between the two. (2) This study examines the value of ecosystem services, the compatibility of water and land resources, and the extent of their coupling and coordination at a municipal level. Nevertheless, issues at the county and township levels must also be resolved. Future research will be focused on examining the characteristics and causes of the relationship between land conversion, ecosystem services, and the alignment of water and land resources at both grid and neighborhood scales while also offering data support for the precise regulation of the balance between the supply and demand of ecosystem services. (3) This paper examines the interdependent relationship between ecosystem services and water and land resources, excluding the impact of external factors such as economic, social, and cultural influences on ESV's development trends and distribution characteristics and the matching coefficients of water and land resources. The study's scope must encompass several external aspects to attain the mutual advantage and win-win scenario of ecological protection and high-quality development inside the watershed.

Conclusions

(1) During the study period, the ESV of the Huaihe River basin grew by 12.294 billion yuan. Water land gives more to the ESV than cultivated land, forest land, grassland, and unused land combined. The ESV of water land rose by 16.107 billion yuan, whereas the ESV of cultivated land, forest land, grassland, and unused land declined by 3.287 billion yuan, 0.411 billion yuan, 0.096 billion yuan, and 0.021 billion yuan, respectively. In the Huaihe River Basin, the average land ESV exhibited a spatial distribution pattern characterized by "elevated in the east and diminished in the west". Lianyungang experienced the most significant rise in average land ESV, totaling 8,700 yuan/hm^2. Nantong experienced the most significant reduction in average land ESV, amounting to 3,800 yuan/hm^2.

(2) Overall, from 2010 to 2020, the matching coefficient of water and land resources in the Huaihe River Basin exhibited an upward trend, characterized by a geographical distribution pattern of "high in the east and low in the west". The degree of change exhibits the traits of "superior in the hinterland compared to the periphery and superior in the north relative to the south". The sub-regional rankings are as follows: the Jiangsu section (0.60) surpasses the Anhui section (0.24), which exceeds the Shandong section (0.20), followed by the Henan section (0.13).

(3) Between 2010 and 2015, the degree of coordination between ESV and the matching coefficients of water and land resources in the Huaihe River Basin diminished from 0.5477 to 0.5087. From 2015 to 2020, it rose to 0.5115 and has since been in a transitional phase. The spatial distribution pattern is characterized by "east high and west low", with the shift primarily indicated as "east positive and west negative". Zhengzhou, Jining, Huaibei, Zhumadian, and Chuzhou have significant declines in coordination levels.

(4) Between 2010 and 2020, the Gini coefficient reflecting the linked coordination degree of ecosystem service value and water and land resource matching coefficients in the Huaihe River Basin increased, indicating a progressive rise in inter-regional disparities. The coupled coordination degree of the Anhui section primarily influences intra-regional divergence, with an average contribution rate of inter-regional variations at 75.36%, serving as the principal source of discrepancies in coordination degree.

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Conflict of Interest

The authors declare there is no conflict.

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