Study on the spatial distribution of water resource value in the agricultural system of the Yellow River Basin

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ABSTRACT

To analyze the spatial distribution characteristics of water resource value in the agricultural system of the Yellow River Basin, this paper takes the Yellow River Basin as its research object and studies the spatial distribution characteristics and influencing factors of water resource value in the agricultural system using the emergy theory and method, the spatial autocorrelation analysis method, and the spatial regression model. The results show the following. (1) The value of water resources in the agricultural system ranges from 0.64 to 0.98 \$/m^3, and the value in the middle and lower reaches of the basin is relatively high. (2) The Moran index of the water resource value in the agricultural system is 0.2772, showing a positive spatial autocorrelation feature. Here, 'high-high (high value city gathering)' is the main aggregation mode, which is mainly concentrated in the middle and lower reaches of the basin. (3) The spatial error model, moreover, has the best simulation effect. The cultivated land area, total agricultural output value, agricultural labor force, and total mechanical power have a significant positive impact on the agricultural production value of water resources in the Yellow River Basin; the altitude, annual average temperature, and agricultural water consumption have a negative impact. Overall, this study shows that guiding the distribution of water resources according to their value and increasing agricultural water use in the middle and lower reaches of the basin will help improve the overall agricultural production efficiency of water resources in the basin.

Key words: Agricultural system, Emergy, Spatial autocorrelation, Yellow River Basin, Water resources

HIGHLIGHTS

- Spatial distribution analysis provides a basis for the formulation of water resources management policies.
- Water resource value in the agricultural system is quantified based on the emergy theory.
- The spatial autocorrelation analysis method is used to analyze the spatial distribution of water resources value.
- The spatial regression model is used to identify the main influencing factors of water resources value.

GRAPHICAL ABSTRACT
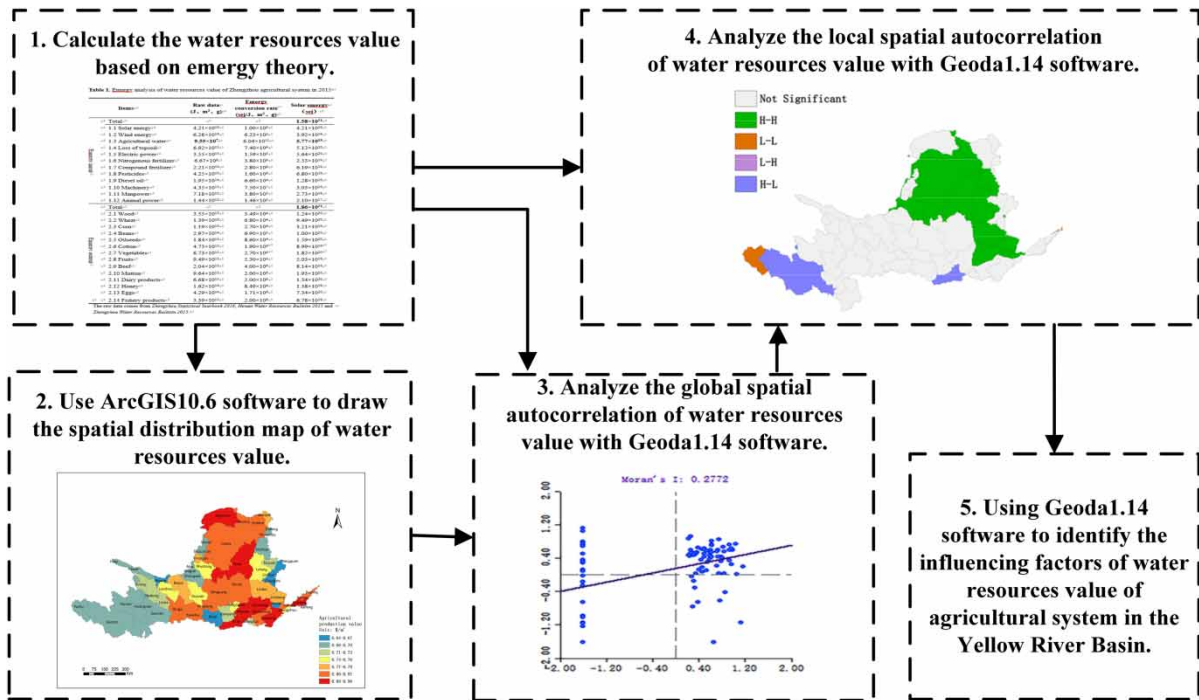
1. INTRODUCTION

Water resource allocation is an important means to realize the effective and equitable distribution of water resources among different regions and water users and thereby achieve the sustainable utilization of water resources (Kama & ECONOMIX, 2001; Wu *et al.*, 2019b). The water resource values in different regions and different water users are the main parameters used to guide the allocation of water resources, as the water consumption of a water user will produce different values in different regions (Wu *et al.*, 2018; Di *et al.*, 2019; Sánchez-Martín *et al.*, 2020). Therefore, the different values and influencing factors of the same water department in different regions can be used to improve the efficiency of water resource allocation. The agricultural system is the main body of water resource allocation. Reasonable distribution of the agricultural water used in the river basin affects the fairness and efficiency of overall water resource allocation (Tian *et al.*, 2020; Zhang *et al.*, 2020). Therefore, it is of great significance to study the spatial distribution of the water resource value in the agricultural system and analyze the influencing factors to ensure the optimal allocation of water resources in the river basin.

There are many methods used to estimate the value of water resources, such as the shadow price method (He *et al.*, 2007; Liu *et al.*, 2009), marginal opportunity cost (Pulido-Velazquez *et al.*, 2013), the CGE model (Nechifor & Winning, 2017), the fuzzy mathematics method of water resource value (Jia *et al.*, 2018), etc. These methods usually make it difficult to consider the natural circulation of water resources, energy conversion, and other natural attributes; they are also unable to objectively and scientifically explain the hydrological cycle process and self-value of natural water resources (Wu *et al.*, 2019a, 2019b). In recent years, Buenfil applied emergy theory to the field of water resources and used the emergy analysis method to simulate and optimize the water allocation of the

three main departments of urban, agriculture, and environment in Florida (Buenfil, 2000). Wu Zening *et al.* used the emergy analysis method to construct an emergy analysis framework for the ecological economic value of regional water resources, which realized a unified measurement of the economic, social, and ecological environment value of water resources and provided a theoretical basis and technical methods for the rational utilization and value accounting of water resources (Wu *et al.*, 2019a). Agriculture is the main water sector of the social economy, and many studies have been conducted around the value of water resources in agricultural systems to analyze the most beneficial composition and accounting method for agricultural water resources (Wang & Wang, 2005). Some studies calculated the water resource value of the Yellow River Basin in four sections via the shadow price method (Di *et al.*, 2019, 2020) but did not analyze the influencing factors underlying the differences in the water resource value of each section. Current research on the value of water resources in agricultural systems mostly ignores the natural attributes of water resources in terms of content and focuses instead of research into provincial (municipal) administrative districts based on time sequences, while studies on the spatial distribution and quantitative identification of the main influencing factors of water resource value in the agricultural system based on the watershed level remain relatively uncommon. The spatial distribution of water resource value and its influencing factors in the basin's agricultural system, therefore, needs further study.

The Yellow River Basin is the second largest basin in China. With 2% of the national river runoff, the Yellow River encompasses 15% of the country's cultivated land area and 12% of the population's water supply tasks. With the development of the social economy, the contradiction between supply and demand of water resources in the Yellow River Basin has intensified year by year. To rationally and efficiently use limited water resources, the optimal allocation of water resources in space has become a long-term goal in the Yellow River Basin. The accurate evaluation and determination of the value and spatial distribution of water resources in the Yellow River Basin is the foundation of the optimal allocation of water resources.

In this research, the uniformly measurable emergy theory of water resource value in the agricultural system and spatial autocorrelation analysis method are combined to study the spatial distribution characteristics and influencing factors of agricultural water resource value in the Yellow River Basin. To begin with, the value of water resources in the agricultural system is quantified based on the actual agricultural water consumption data of cities in the Yellow River Basin in 2015. Secondly, the emergy analysis method and spatial autocorrelation analysis method are combined to analyze the spatial distribution and aggregation characteristics of water resource value in the agricultural system of the Yellow River Basin. Finally, the spatial regression model is used to identify the main influencing factors of water resource value in the agricultural system, which provided the decision-making basis for water resources management and rational allocation.

2. METHODS AND MATERIALS

2.1. Research method

2.1.1. Emergy theory and method

Emergy refers to the amount of another type of energy contained in flowing or stored energy, which is essentially a type of coating energy. The amount of solar energy that forms the direct or indirect application of any resource, product, or labor service is its 'solar emergy' (*EM*) (Odum, 1996), whose unit is the solar Joule (seJ). The calculation formula for *EM* is as follows:

$$EM = \tau \times B \tag{1}$$

where *EM* is the solar emergy (seJ); τ is the emergy conversion rate (seJ/J or seJ/g); and *B* is the energy or mass of the substance (J or g).

The value of water resources in an agricultural system is defined as the contribution of unit water resources to agricultural production in the form of currency (Lv & Wu, 2009). The greater the value of the water resources in the agricultural system is, the higher the benefit of unilateral water to agricultural production. The calculation formula is as follows:

$$EM_{\$PA} = \frac{EM_{AW} \cdot EM_{AY}}{EM_{AU} \cdot W_A \cdot EDR} \tag{2}$$

where $EM\$_{PA}$ is the value of water resources in the agricultural system ($/m^3); EM_{AY} is the agricultural output solar emergy (seJ); EM_{AW} is the agricultural water solar emergy (seJ); EM_{AU} is the agricultural input solar emergy (seJ); W_A is the agricultural water consumption (m^3); and EDR is the emergy/currency ratio (seJ/$).

2.1.2. Spatial autocorrelation analysis

The spatial autocorrelation analysis method has a unique advantage in revealing the correlation between the value of regional water resources and the value of water resources in neighboring areas (Iman *et al.*, 2017). The value of water resources in an agricultural system is closely related to natural factors, such as topography, climate, crop type, etc. and is also affected by social–economic conditions, such as the irrigation level and mode of operation. The above factors generally show geographical similarities. In addition, the Yellow River is the main source of irrigation water for agricultural production in the Yellow River Basin, which is another reason for the spatial correlation in the value of water resources in the basin's agricultural system.

Global spatial autocorrelation is used to analyze the overall spatial correlation degree of the water resource value in the agricultural system of the Yellow River Basin and determine whether there is spatial agglomeration. Moran's index I is commonly used for such characterizations, and the calculation formula is as follows (Yongxiu *et al.*, 2018):

$$I = \frac{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} \omega_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \left(\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} \omega_{ij} \right)} \tag{3}$$

where I is Moran's index, x_i is the value of the agricultural system water resources of city i in the river basin, n is the number of provinces (regions), and w_{ij} is the spatial weight matrix: If i is adjacent to j, the weight is set to 1; otherwise, it is 0. $I > 0$ indicates a positive correlation with a positive homogeneous spatial agglomeration effect; the closer the result is to 1, the more obvious the spatial agglomeration effect is. If $I = 0$, there is no correlation (no spatial correlation). $I < 0$ indicates a negative correlation, demonstrating that there are significant differences in the whole; the closer the result is to -1, the more significant the spatial differences are. $\overline{x}$ is the average value of the water resource value of the basin's agricultural system, and S^2 is the variance of the water resource value of the basin's agricultural system.

Local spatial autocorrelation mainly investigates the spatial agglomeration degree of the water resource value of the agricultural system in a certain city and neighboring cities in the basin. Using local spatial autocorrelation analysis, we can determine the spatial aggregation type and location of the water resource value in the agricultural system of the Yellow River Basin, which is usually characterized by the local Moran's index I (Taghipour *et al.*, 2014). The calculation formula is as follows:

$$I_i = \frac{(x_i - \overline{x}) \sum\limits_{j=1}^{n} \omega_{ij}(x_i - \overline{x})}{S^2} \tag{4}$$

where I_i represents the local Moran's index, and other symbols and meanings are the same as before.

In practical research, Moran scatter plots and local indicators of spatial associations (LISA) agglomeration map are often used for local spatial autocorrelation analyses (Iman *et al*., 2017). In this study, the four quadrants of the Moran scatter plot correspond to the spatial connection form of the water resource values of the agricultural systems in various cities in the river basin. The Moran scatter diagram is divided into four quadrants. The first quadrant is the 'High–High (H-H)' correlation mode – that is, a cluster of the high-value cities; the second quadrant is the 'Low–High (L-H)' correlation mode – that is, the high-value cities that surround the low-value cities; the third *q* is the 'Low–Low (L-L)' correlation mode – that is, a cluster of the low-value cities, and the fourth is the 'High–Low (H-L)' correlation mode – that is, the low-value cities that surround the high-value cities.

Unlike the global Moran's index, a Moran scatter plot can identify the spatial aggregation patterns of the water resource values of agricultural systems in different cities in the basin, while the LISA aggregation map can show the location of spatial aggregation (Srikanta *et al*., 2020).

2.1.3. Spatial regression model

The spatial lag model (SLM) and the spatial error model (SEM) are two basic spatial regression models (Tobler *et al*., 2015) used to ensure that the parameter estimation of the classical regression model (SLRM) is not biased and inconsistent when the agricultural production value of water resources in the Yellow River Basin has a spatial effect that cannot be ignored. The SLM adds the spatial lag term of the water resource value in the agricultural system of the Yellow River basin into the general panel data model, indicating that the influencing factors of the water resource value of the agricultural system in a certain city are affected by the influencing factors of the neighboring cities; the spatial error model (SEM) adds the error term of the spatial correlation; that is, the error term of a certain city model is affected by the error term of the neighboring city model. Further, the intensity affected by neighboring cities is expressed by the spatial weight matrix. The SLM and SEM for the water resource value in the agricultural system of the Yellow River Basin are as follows (Peili & Lijie, 2015):

$$Y = \rho W_y + \beta X + \delta \tag{5}$$

where Y represents the agricultural production value of water resources (\$/m^3), ρ is the spatial lag regression coefficient, W_y is the spatial lag factor with weight; X is the influencing factor, β is the regression coefficient, and δ is the independent error term.

$$Y = \alpha X + \varepsilon \tag{6}$$

$$\varepsilon = \lambda \cdot \varepsilon W_\varepsilon + M \tag{7}$$

where X and Y have the same meaning as formula (5), α is the coefficient of influencing factors, ε is the random error term, λ is the regression coefficient of the spatial error term, $\varepsilon W_\varepsilon$ is the spatial error term, W_ε is the spatial weight matrix of the error term, and M is the random error vector.

2.1.4. Research framework

The objective of this paper is to analyze the spatial distribution characteristics and influencing factors of water resource value in the agricultural system of the Yellow River Basin. According to the above research methods, the research framework of this paper is constructed as shown in Figure 1. Firstly, the economy, society, and water consumption data in the Yellow River Basin are collected, and the emergy analysis table of water resource value in the agricultural system is compiled. The spatial distribution map of water resource value of the agricultural system in the Yellow River Basin is drawn by ArcGIS 10.6 software. Then, the calculation results of water
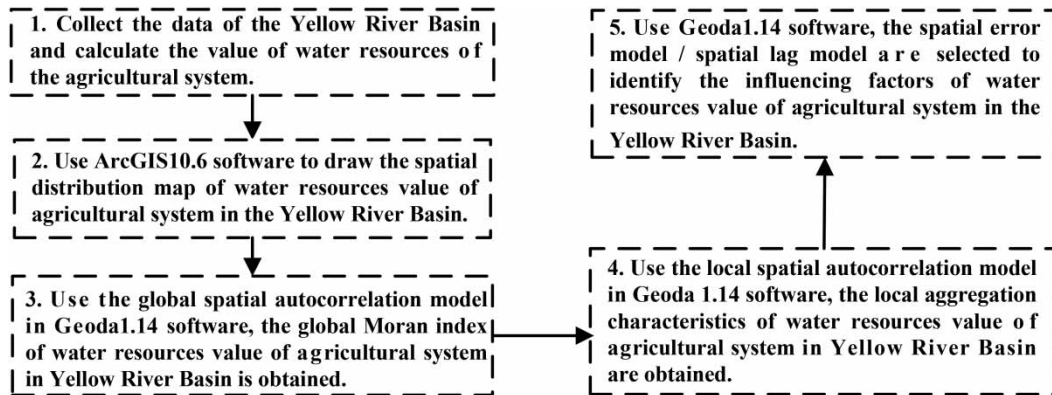
Fig. 1. | Research framework of study on the spatial distribution of water resource value in the agricultural system of the Yellow River Basin.

resource value of the agricultural system in the Yellow River Basin are input into Geoda1.14 software in the form of data. Using the global spatial autocorrelation model (see Section 2.1.2), the global Moran index I of water resource value in the agricultural system of the Yellow River basin can be obtained. As the global Moran index can only reflect the spatial agglomeration of water resource value in the agricultural system of the Yellow River Basin, in order to further explore the clustering and heterogeneity of water resource value in the local space of the agricultural system in the Yellow River Basin, the local spatial autocorrelation model of Geoda1.14 software is used to obtain the local aggregation characteristics of water resource value in the agricultural system of the Yellow River Basin. Finally, the regression model based on spatial weight matrix (including SEM and SLM) is used to analyze the influencing factors of water resource value in agricultural system of the Yellow River Basin by using Geoda1.14 software.

2.2. Study area

The Yellow River Basin is located in the north central part of China. The altitude difference in this area is large, as is the temperature difference. The average annual precipitation of the basin is 445.8 mm. At the same time, the Yellow River contains the greatest amount of sediment in the world. Therefore, limited water resources must also undertake the sediment transport tasks that the general clear water river does not have, which further reduces the amount of water that can be used for economic and social development. Moreover, the shortage of water resources is serious. The water resources of each province in the Yellow River Basin also vary greatly, and the spatial distribution of water resources is uneven. The Ningmeng Hetao irrigation area in the upper reaches, Fenwei River Valley irrigation area in the middle reaches, and Yellow River Diversion irrigation Area in the lower reaches are important agricultural areas in China. The effective irrigation area is 5,176,400 hm^2, the irrigation rate of cultivated land is 31.9%, and the per capita irrigation area in rural areas is 0.0753 hm^2 (Figure 2). The main crops are corn, wheat, cotton, oil, etc. Agricultural production is a major water user in the Yellow River Basin. The presence of less water and more sand, the interruption of tributaries, and the overexploitation of groundwater have produced adverse effects on agricultural production in the Yellow River Basin. In addition, the population growth, accelerated urbanization, and rapid industrial development in the area have caused the proportion of agricultural water consumption in the Yellow River Basin to decrease year by year, resulting in increasingly more serious water shortages.
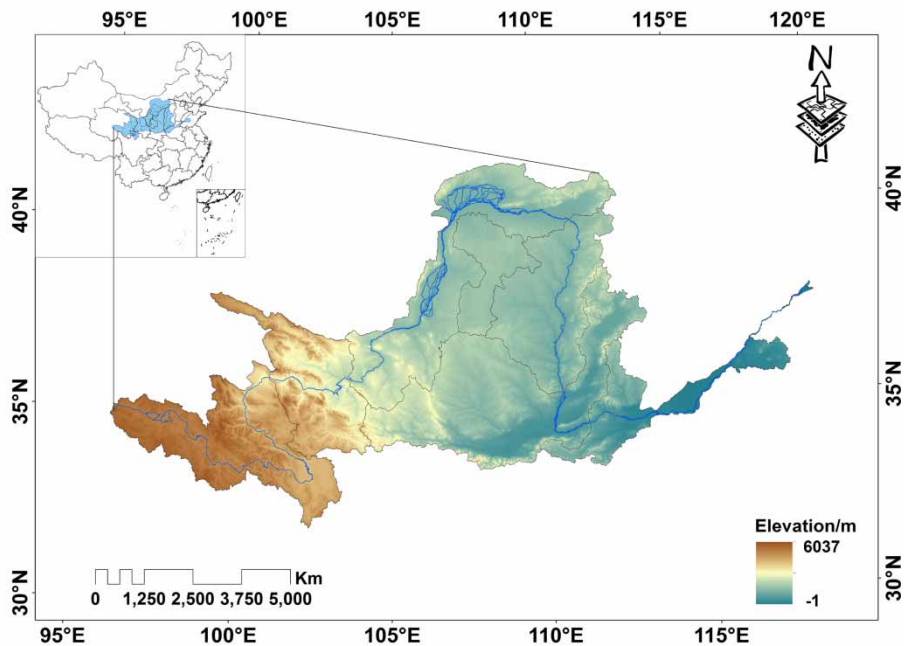
Fig. 2. | Location of the study area.

2.3. Data sources

Considering the consistency of regional space and the availability of data, this paper defines its research scope as 59 cities in the Yellow River Basin. The research's time period encompasses the year 2015. The water consumption data required for this study come from the 'China Water Conservancy Statistical Yearbook 2016' (Lv & Wu, 2009), 'Water Resources Bulletin 2015 of the Yellow River Basin', and municipalities 'Water Resources Bulletin 2015'. The data required for the quantification of emergy come from the 'China Agricultural Statistical Yearbook 2016', the provincial 'Statistical Yearbooks', and the 'Statistical Yearbooks' of various cities. The emergy/currency ratio comes from the literature (Di et al., 2019, 2020; Wu et al., 2019a).

According to the quantitative formula for the emergy of water resources, the value of water resources in an agricultural system is related to water consumption, the emergy/currency ratio, and the input and output of each economic system. Therefore, it is necessary to consider two major indicators of agricultural water consumption and total agricultural output value when selecting the main influencing factors. Based on a summary of the existing relevant research, combined with the basic principles for the selection of influencing factors, the agricultural production conditions of the Yellow River Basin and the availability of data, the altitude (X_1), annual average temperature (X_2), cultivated land area (X_3), agricultural water consumption (X_4), total agricultural output value (X_5), labor force (X_6), total mechanical power (X_7), and chemical fertilizer (X_8) are selected as influencing factors.

3. RESULTS AND ANALYSIS

3.1. Quantification of the water resource value in the agricultural system

Agricultural production is inseparable from water. To analyze the transfer and transformation process of water resources in agricultural systems, it is necessary to clarify the input and output of energy and materials in the

process of agricultural production. According to the collected raw data and corresponding emergy conversion rates (Lan *et al*., 2002), the emergy of various ecological flows can be quantified. Taking Zhengzhou in Central China as an example, an emergy analysis table of the agricultural system is shown in Table 1.

In 2015, the total energy input of Zhengzhou was 1.58×10^{21} seJ, where the agricultural water input was 5.77×10^{19} seJ. The total emergy output was 1.86×10^{21} seJ. Agricultural products with the largest share of emergy output included wheat, eggs, mutton, vegetables, and oilseeds; their emergy outputs were 9.49×10^{20} seJ, 7.34×10^{20} seJ, 1.93×10^{20} seJ, 1.82×10^{20} seJ, and 1.59×10^{20} seJ, respectively. Among them, wheat contributed the largest share, accounting for 51.02% of the total emergy output. In 2015, the emergy output of the Zhengzhou agricultural system was greater than its input, thereby ensuring the ongoing cycle of the system. The main emergy indicators of the water resource value for the Zhengzhou agricultural system in 2015 are summarized in Table 2.

The value of water resources in the Zhengzhou agricultural system is quantified as 0.76 \$/m^3 by bringing the calculation results of Tables 1 and 2 into formula (2). The values of the water resources of agricultural systems in other cities of the Yellow River basin can then be obtained, and the results are shown in Table 3.

Table 1. | Emergy analysis of water resource value of Zhengzhou agricultural system in 2015.

Items		Raw data (J m^3, g)	Emergy conversion rate (seJ/J m^3, g)	Solar emergy (seJ)
Emergy input	Total			1.58×10^{21}
	1.1 Solar energy	4.21×10^{19}	1.00×10^{0}	4.21×10^{19}
	1.2 Wind energy	6.28×10^{16}	6.23×10^{2}	3.92×10^{19}
	1.3 Agricultural water	9.55×10^{7}	6.04×10^{11}	5.77×10^{19}
	1.4 Loss of topsoil	6.92×10^{15}	7.40×10^{4}	5.12×10^{20}
	1.5 Electric power	3.55×10^{15}	1.59×10^{5}	5.64×10^{20}
	1.6 Nitrogenous fertilizer	6.67×10^{9}	3.80×10^{9}	2.53×10^{19}
	1.7 Compound fertilizer	2.21×10^{10}	2.80×10^{9}	6.19×10^{19}
	1.8 Pesticides	4.25×10^{10}	1.60×10^{9}	6.80×10^{19}
	1.9 Diesel oil	1.95×10^{14}	6.60×10^{4}	1.28×10^{19}
	1.10 Machinery	4.35×10^{11}	7.50×10^{7}	3.03×10^{19}
	1.11 Manpower	7.18×10^{12}	3.80×10^{5}	2.73×10^{18}
	1.12 Animal power	1.44×10^{12}	1.46×10^{5}	2.10×10^{17}
Emergy output	Total			1.86×10^{21}
	2.1 Wood	3.55×10^{15}	3.49×10^{4}	1.24×10^{20}
	2.2 Wheat	1.39×10^{16}	6.80×10^{4}	9.49×10^{20}
	2.3 Corn	1.19×10^{15}	2.70×10^{4}	3.21×10^{19}
	2.4 Beans	2.97×10^{14}	6.90×10^{5}	1.00×10^{20}
	2.5 Oilseeds	1.84×10^{15}	8.60×10^{4}	1.59×10^{20}
	2.6 Cotton	4.73×10^{13}	1.90×10^{6}	8.99×10^{19}
	2.7 Vegetables	6.73×10^{15}	2.70×10^{4}	1.82×10^{20}
	2.8 Fruits	9.49×10^{13}	5.30×10^{4}	5.03×10^{18}
	2.9 Beef	2.04×10^{13}	4.00×10^{6}	8.14×10^{19}
	2.10 Mutton	9.64×10^{13}	2.00×10^{6}	1.93×10^{20}
	2.11 Dairy products	6.68×10^{13}	2.00×10^{6}	1.34×10^{20}
	2.12 Honey	1.62×10^{14}	8.49×10^{4}	1.38×10^{19}
	2.13 Eggs	4.29×10^{14}	1.71×10^{6}	7.34×10^{20}
	2.14 Fishery products	3.39×10^{12}	2.00×10^{6}	6.78×10^{18}

The raw data come from Zhengzhou Statistical Yearbook 2016, Henan Water Resources Bulletin 2015 and Zhengzhou Water Resources Bulletin 2015.

Table 2. | Summary of main emergy indicators of agricultural production value of water resource in Zhengzhou in 2015.

Emergy indicators	Solar emergy
Emergy input (EM_{AY})	1.58×10^{21} seJ
Emergy output (EM_{AU})	1.86×10^{21} seJ
Agricultural water emergy (EM_{AW})	5.77×10^{19} seJ
Agricultural water consumption (EM_A)	9.55×10^7 m^3
Emergy/currency ratio	2.39×10^{10} seJ/$

Table 3. | Summary of agricultural production value of water resources in all cities of the Yellow River Basin in 2015 unit: $/m^3.

Cities	Value	Cities	Value	Cities	Value	Cities	Value
Hainan	0.69	Gannan	0.69	Tongchuan	0.75	Lvliang	0.75
Haidong	0.71	Lanzhou	0.74	Baoji	0.64	Jinzhong	0.66
Haibei	0.69	Wuzhong	0.76	Xianyang	0.73	Linfen	0.79
Huangnan	0.68	Shizuishan	0.68	Weinan	0.98	Yuncheng	0.93
Guoluo	0.67	Zhongwei	0.70	Yulin	0.91	Taiyuan	0.73
Yushu	0.68	Guyuan	0.74	Shangluo	0.72	Anyang	0.83
Haixi	0.66	Yinchuan	0.77	Yangling	0.75	Kaifeng	0.67
Xining	0.72	Hohhot	0.87	Hancheng	0.76	Luoyang	0.94
Wuwei	0.65	Baotou	0.83	Xi'an	0.96	Puyang	0.84
Linxia	0.73	Wuhai	0.69	Shuozhou	0.69	Xinxiang	0.91
Baiyin	0.78	Ulanqab	0.78	Datong	0.65	Jiaozuo	0.86
Dingxi	0.82	Bayannur	0.91	Yangquan	0.75	Sanmenxia	0.85
Tianshui	0.87	Alxa League	0.68	Changzhi	0.66	Jiyuan	0.64
Pingliang	0.86	Ordos	0.83	Jincheng	0.78	Zhengzhou	0.76
Qingyang	0.84	Yan'an	0.85	Xinzhou	0.70		

There are differences in the value of water resources in the agricultural systems in cities across the Yellow River Basin. To analyze the spatial distribution characteristics of the water resource values in these agricultural systems, a spatial distribution map of the water resource value is provided (Figure 3).

The water resource value in the agricultural system of the Yellow River Basin is in the range of 0.64–0.98 $/m^3. Here, Weinan City has the highest value, and Baoji City has the lowest value. There is a large gap in the value of water resources in the agricultural systems of all cities. From the perspective of the river basin, the spatial distribution of the water resource values in the agricultural system is unbalanced. The value of water resources in the middle and lower reaches is higher, and the value in the upper reaches is lower. The reasons for the high value of water resources in the middle and lower reaches of the river basin are as follows: (1) the middle and lower reaches have better water and heat conditions, rich land resources, fertile soil, and are suitable for crop growth; (2) the water-saving irrigation technology is relatively advanced, and a large number of mechanized operations improve agricultural production efficiency; (3) the economy is relatively developed, resulting in the development of agricultural production. The reasons for the low value of water resources in the agricultural
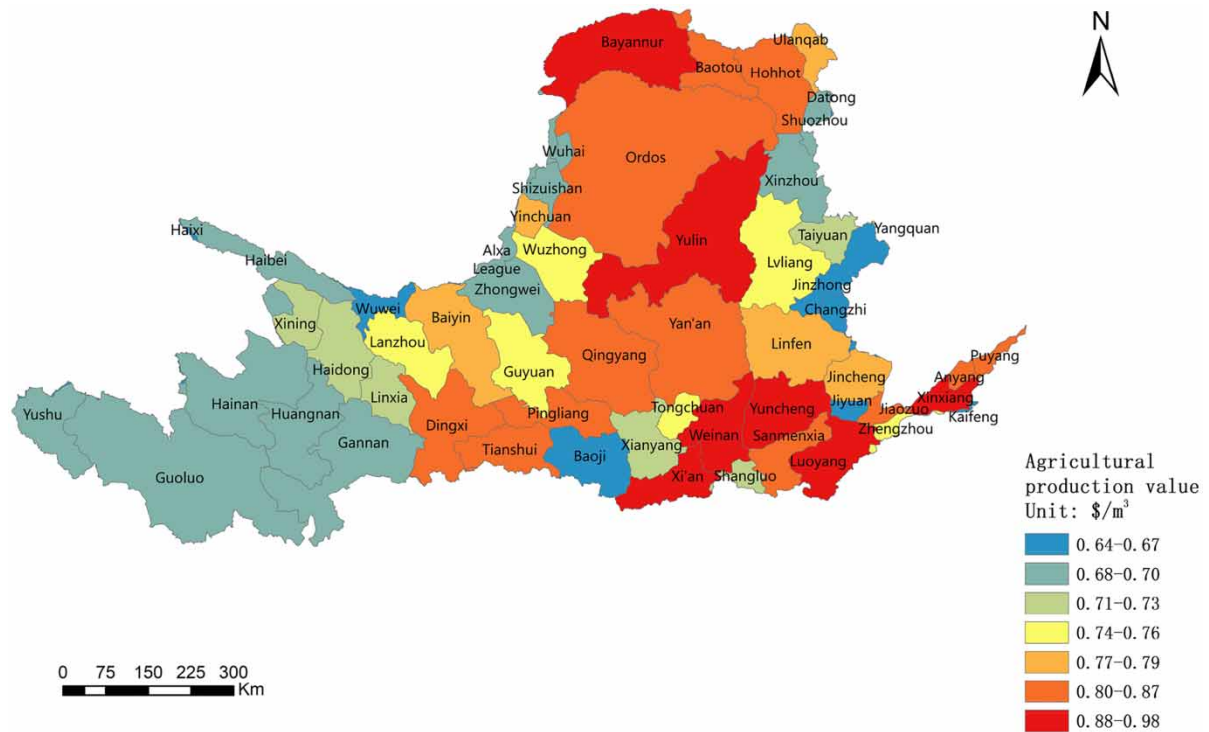
Fig. 3. | Spatial distribution of water resource value in the agricultural system of the Yellow River Basin.

system in the headwaters of the river basin are as follows: (1) the headwaters of the river basin belong to the alpine region with a high altitude and low temperature, and the grain production in the area is greatly affected by natural conditions, so the output is low; (2) the land is sparsely populated, the labor force is insufficient, and the agricultural production efficiency is low. Moreover, transportation is inconvenient, thereby increasing the cost of the grain output; (3) the regional economy is underdeveloped, the level of agricultural modernization is low, and the proportion of natural resources invested in agricultural production is significant.

3.2. Spatial autocorrelation analysis of the water resource value in the agricultural system

The water resource values in the agricultural system of cities in the Yellow River Basin in Table 3 are input into Geoda1.14 software in the form of SHAPE file and by using the formula (3), the global Moran's Index I of the water resource value for the agricultural system in the Yellow River Basin can be calculated as 0.2772, indicating that the water resource value of the agricultural system in the Yellow River Basin has a strong spatially positive correlation. However, since the global Moran's index can only reflect the overall spatial concentration of the water resource value of the agricultural system, to further investigate the clustering and heterogeneity of the water resource value of the agricultural system in a local space, it is necessary to carry out a local spatial autocorrelation analysis of the water resource value of the Yellow River Basin. The results are shown in Figures 4 and 5.

There are 28 cities in the first quadrant of the Moran scatter plot, and 13, 9, and 9 cities in the second, third, and fourth quadrants, respectively. According to the method in Section 2.1.2 Spatial autocorrelation analysis, the value of water resources in the agricultural system of the Yellow River Basin mainly assumes the form of 'H-H (a cluster of the high value cities)', with a small amount of the L-L (a cluster of the low value cities)' type,
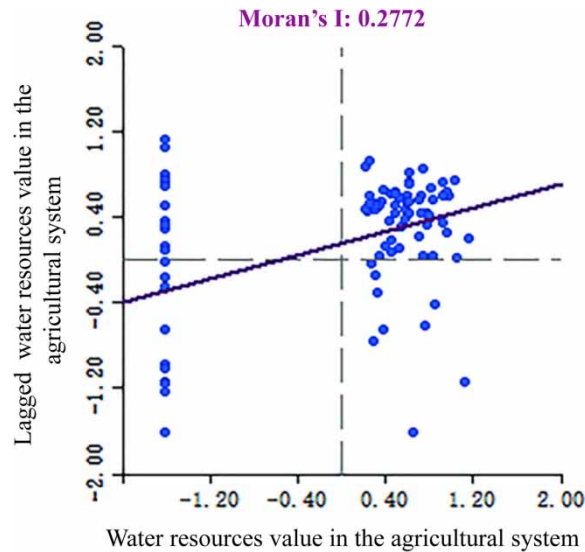
Fig. 4. | Moran scatter plot of water resource value of the agricultural system in the Yellow River Basin.
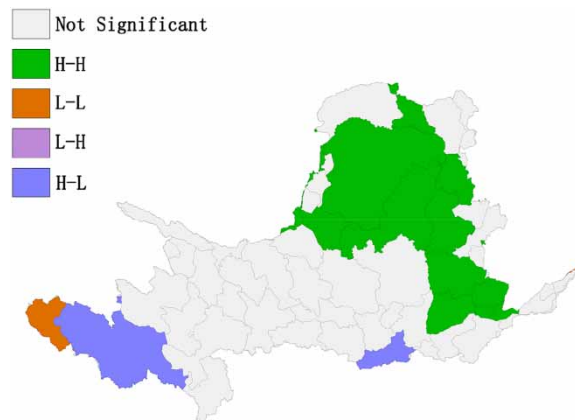
Fig. 5. | LISA agglomeration map of water resource value of the agricultural system in the Yellow River Basin.

'L-H (the high value cities that surround the low value cities)' type, and 'H-L (the low value cities that surround the high value cities)' type. This is consistent with the estimation results of the global Moran's index, and the water resource value of the agricultural system is positively correlated in space. Figure 5 shows that the 'H-H' aggregation area is mainly located in the middle and lower reaches of the Yellow River Basin, the 'L-L' aggregation area is mainly concentrated at the source of the Yellow River Basin, and the 'H-L' aggregation areas are scattered in the upper and middle reaches of the Yellow River.

3.3. Analysis of the main influencing factors of water resource value in the agricultural system

The agricultural production value of water resources in the Yellow River Basin is positively correlated in space. According to the input–output situation of the agricultural system in the emergy analysis table, the premise that

the dependent variable is not spatially independent should be fully considered when choosing to model that variable, and the inter-regional relationship should also be introduced into the model. Thus, a regression model based on the spatial weight matrix is used. The Geoda1.14 software was used to test the spatial effect of the water resource value of the agricultural system in the Yellow River Basin. The results are shown in Table 4.

According to Table 4, the P values of LMLAG and LMERR are 0.0487 and 0.0165, respectively, both of which are significant at a level of 5%. However, the statistic for R-LMERR is 6.2621, which is larger than the 3.8974 of R-LMLAG, making it more appropriate to build the SEM model. In the simulation process, since the test results of fertilizer consumption are not significant, the regression results of the SEM model are shown after elimination (Table 5).

It can be seen from Table 5 that the spatial regression coefficient λ is significantly positive, indicating that the agricultural production value of water resources in the Yellow River Basin is significantly affected by the agricultural production value of water resources in neighboring cities. The agricultural production value of water resources in the Yellow River Basin has obvious spatial spillover. Thus, for every 1% change in the agricultural production value of water resources in neighboring cities, the value of the local city will change by 0.4722% in the same direction.

The regression coefficients of altitude (X_1) and annual average temperature (X_2) are -0.2974 and -0.4633, respectively, at a 1% level of significance, indicating that the agricultural production value of water resources in the Yellow River Basin is negatively correlated with altitude and annual average temperature. Altitude and temperature are important factors that reflect the distribution of moisture and heat in a certain place. The topography of the

Table 4. | Spatial effect test of agricultural value of water resources in the Yellow River Basin.

Test statistics	Statistics	P value
Lagrange multiplier (lag)	0.3970	0.0487
Robust LM (lag)	3.8974	0.0484
Lagrange multiplier (error)	2.7617	0.0165
Robust LM (error)	6.2621	0.0123

Table 5. | Regression results of spatial error model.

Variable	Correlation coefficient	P value
λ	0.4722*	0.0000
X_1	-0.2974*	0.0000
X_2	-0.4633*	0.0085
X_3	0.0405***	0.0809
X_4	-0.1009*	0.0008
X_5	0.2007**	0.0357
X_6	0.0261**	0.0355
X_7	0.2158***	0.0905
C	0.1404**	0.0368

*, **, ***, respectively, are significant at 1, 5 and 10% levels.

Yellow River Basin is complex. The altitude of the Qinghai–Tibet Plateau in the first step is 3,000–5,000 m. Except for the valley in the southeast of the plateau, the average annual temperature is mostly lower than 5°C. The elevation of the impact plain in the third step is mostly below 100 m, and the average annual temperature is 11–14°C. The altitude difference in the basin is large, as is the temperature difference. The higher the altitude is, the colder the climate is, and the more unfavorable it becomes for the growth of crops. A lack of heat, strong wind, etc., will also affect the output of crops, thus affecting the agricultural production value of water resources in the basin.

The unit contribution rate of cultivated land area (X_3) in the model is only 0.0405. With the advancement of science and technology, agricultural production no longer involves extensive cultivation. We can increase grain production by increasing the yield per micrometer instead of engaging in large-scale sowing.

At a 1% significance level, for every 1% increase in agricultural water consumption (X_4), the agricultural production value of water resources in the Yellow River Basin will decrease by 0.1009%, which presents a negative correlation. For certain agricultural output benefits, the greater the water consumption is, the lower the efficiency of water resource utilization, and the lower the value of water resources.

Under the condition of a 5% significance level, for every 1% increase in total agricultural output value (X_5), the agricultural production value of water resources in the Yellow River Basin will increase by 0.2007%, which indicates a positive correlation. The total agricultural output value is the wind vane of regional agricultural economic development. The higher the output value is, the lower the emergy/currency ratio is, and the higher the contribution of unit water resources to production becomes, which can be seen in formula (4).

The influence of labor force (X_6) and total mechanical power (X_7) on the agricultural production value of water resources in the Yellow River Basin (0.0261 and 0.2158, respectively) conforms to the characteristics of agricultural production mechanization. In the process of agricultural modernization, pumps, seeders, harvesters, sprayers, tractors, and agricultural vehicles are widely used in irrigation, sowing, harvesting, field management, agricultural product transportation, and other various operations, making agricultural production mainly rely on machinery rather than manpower. Agricultural mechanization not only saves labor but also greatly improves labor production efficiency and obtains a higher agricultural production value from the water resources.

After introducing the spatial lag term, the absolute values of the correlation coefficients of X_1, X_2, X_3, and X_4 can be seen to decrease from the values before the introduction, while X_5, X_6, and X_7 increase from the values before the introduction. Under the synergistic effect of space, the influence of social and economic factors on the agricultural production value of water resources is greater than that of natural geographical factors. This occurs because agricultural modernization has overcome the limitations of natural geographical conditions on agricultural production, greatly improving the efficiency of agricultural production, as well as the value of the agricultural production of water resources.

4. CONCLUSION

1. Emergy theory gives us a new way to understand the water resource value in the agricultural system of the Yellow River basin. The emergy analysis method is used to quantify the value of water resources in the agricultural system of the river basin, which solves the problem of the low values caused by neglecting the basin's natural attributes (found in most previous studies on water resources). In this paper, the spatial autocorrelation analysis method and spatial lag regression model were used to determine the influence of spatial geographical characteristics on the spatial distribution of the water resource value from the perspective of the entire river basin, which surpasses the limitations of previous studies on water resource value, which mostly concentrated on the provincial administrative region or the municipal administrative region.

2. This study has practical guiding significance for water distribution in the Yellow River Basin. The cities with a high value of water resources in the basin's agricultural system are mainly concentrated in the middle and

lower reaches of the basin. Taking the value of water resources in the agricultural system as a guide, properly increasing the distribution of agricultural water in the middle and lower reaches of the basin will contribute to the efficient utilization of water resources and improve production efficiency in the basin's agricultural system.

3. This paper demonstrates the feasibility studying the value and spatial distribution of water resources in the agricultural system of the Yellow River Basin using emergy and spatial autocorrelation analyses. Combining emergy value theory with spatial autocorrelation analysis method to analyze the spatial distribution and aggregation characteristics of water resource value is also applicable to other regions and other basins. However, this study only analyzed the spatial changes and main influencing factors of the water resource value for the agricultural system in the Yellow River Basin during 2015. Thus, further studies are needed to investigate the trends of changes in the water resource value and analyze the main influencing factors from the time dimension.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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