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Dynamic evolution of spatial equilibrium degree of water resources composite system in system-region two stages: The case of Lianshui Basin, China

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ABSTRACT

The water resources in Lianshui Basin is facing a prominent contradiction between production and ecology, as well as fierce competition among various regions. However, existing researches on spatial equilibrium typically tend to address only one of the dimensions among water resources system and other systems or among different regions, which can not meet the requirements for optimal allocation of water resources aiming for spatial equilibrium under the high-quality development strategy. The definition and quantitative evaluation method of spatial equilibrium remain unclear. In order to respond to the policy of spatial equilibrium and overcome the dilemma of water resources development and utilization under the new normal, the connotation of spatial equilibrium at two levels of system and region was presented, a quantitative dynamic evaluation method for the spatial equilibrium degree in system-region two stages was proposed in this study. A comprehensive evaluation indicators system was built for the water resources composite system composed of three subsystems: water resources, social economy and ecological environment, and a dynamic quantization model of coupling coordination degree based on the comprehensive evaluation indices of three subsystems was established, the temporal and spatial dynamic evolution process of the coupling coordination degree of water resources composite system was analyzed. At the same time, Theil index was used to research the dynamic evolution characteristics of the regional difference in coupling coordination degree in Lianshui Basin. This paper also identified the main source of difference based on the decomposition of Theil index, and the degree and trend of spatial equilibrium of water resources in Lianshui Basin were comprehensively analyzed. The results showed that the coupling coordination degree of the composite system of each district in Lianshui Basin was continuously improving, but there was no significant trend in the difference of coupling coordination degree among regions, which means the degree of spatial equilibrium in the "system stage" has notably improved, but the degree of spatial equilibrium in the "region stage" had no significant and stable increase. In addition, the difference within the region was always the main reason for the deficiency of spatial equilibrium.

1. Introduction

With the rapid development of the global economy, the development and utilization of water resources are facing both old and new problems. The old problems are mainly insufficient water resources, water ecological damage and water environmental pollution (Rusca et al., 2012). The new problems are manifested in the uncoordinated pattern and unregulated structure among water resources, social economy and ecological environment (Wang et al., 2014). Coupled with global climate change and the impact of human activities, water resources problems have becoming more and more serious. With the development of economy and society, the increasing attention attached to ecological environment, and changes in the supply–demand relationship of water resources, these old and new problems of water resources have become the key constraints in the development, and the sustainable utilization of water resources has become a strategic issue. Standing on the strategic

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height of sustainable development, Chinese President Xi put forward the scientific water management idea of “spatial equilibrium” in 2014 for the first time to ensure national water security (Bai et al., 2022), which has become the guiding principle for solving current water resources problems and supporting regional sustainable development. Under the Chinese new normal, only by adhering to the principle of “spatial equilibrium” can we effectively solve the overload problem of water resources and promote the sustainable development and utilization of water resources.

Due to its geographical location and strategic positioning, Hunan Province has become an important component and key pivot for the country to promote high-quality development in the new phase, while Lianshui Basin, located in the central-eastern part of Hunan Province, still has many shortcomings that need to be overcome. The water resources in Lianshui Basin face a prominent contradiction between various water using departments and fierce competition among various regions. In 2019, the per capita GDP of Lianshui Basin exceeded the per capita value of Hunan Province, but the per capita water resources were only half of the per capita value of Hunan Province. Heng-Shao-Lou arid corridor region contributed about one-third of the province’s grain output, but the water resources conditions are poor in this region, and the agricultural water shortage exceeded 10%. In addition, ecological water is seriously squeezed and pollution problems persist for a long time. Due to the encroachment of human activities on the water resources and excessive development of shorelines, the ecological protection and management of rivers and lakes are under increasing pressure. The satisfaction rate of the ecological flow of important rivers and lakes is insufficient. With the rapid development of human society, the main contradictions among social economy, water resources and ecological environment have taken on new characteristics (Bian et al., 2022a; Luo and Zuo, 2019). New problems such as the mismatch between the development of the three subsystems, and the unbalanced and insufficient development among each region have emerged (Gunasekara et al., 2014; He et al., 2019). The Chang-Zhu-Tan urban agglomeration contributed nearly half of the province’s GDP, but the development and utilization rate of water resources has exceeded the international warning line. The sustainable utilization of water resources has become a strategic issue in socioeconomic development and ecological environmental protection (Murray et al., 2012; Xu et al., 2018). It is urgent to build a spatially equilibrious water resources development and utilization pattern (Li et al., 2022) and resolve the above conflicts through the water control ideology of spatial equilibrium to promote local sustainable development.

The connotation of spatial equilibrium has been interpreted by many scholars (Yang et al., 2022a, 2022b), but there is still no unified conclusion. This paper proposed that the water resources spatial equilibrium is a relatively stable equilibrium state for the composite system of water resources, social economy and ecological environment in a certain region, and also reaches equilibrium in the spatial distribution. In other words, spatial equilibrium should first satisfy the coordinated development of the three subsystems of water resources, social economy and ecological environment within each region, and then further realize the balanced development among all regions.This paper took this as the goal to examine and guide the development and utilization of water resources.

Although there have been many studies on the spatial equilibrium of water resources (Zhou et al., 2022), the quantitative evaluation of the spatial equilibrium is still in an exploratory stage (Niu et al., 2022). Scholars have tried various methods to quantify the spatial equilibrium, but a complete and unified evaluation system and the standard have not yet been formed. Many scholars used the coupled coordination degree analysis to evaluate the degree of coordinated development among different systems (Dehui et al., 2022; Lili et al., 2022). The coupling and coordination degrees between water resources subsystems and other subsystems were obtained using a dynamic coupling coordination model in some academic studies (Cheng et al., 2019). As for the equity of water allocation among different regions, Gini coefficient (Dai et al., 2018) and Theil index (Tu and Guo, 2016) were also used to analyze the fairness of regional water use. At present, the research on spatial equilibrium in Lianshui Basin is still weak. The existing quantitative studies of spatial equilibrium tend to discuss either singularly the degree of coordinated development between water resources and other subsystems like society, economy and other resources in a particular region (Kalantari et al., 2019; Yang et al., 2022a, 2022b), or singularly the degree of equilibrium of water resources development level in different regions (Liming et al., 2022; Bian et al., 2022b). Therefore, it is difficult to take the spatial equilibrium among systems and regions into account at the same time. The spatial equilibrium evaluation model, which only focuses on one aspect of systems or regions, cannot provide the robust support for the allocation process of water resources that simultaneously pursues the coordination of composite system and regional equity. Consequently, in the process of water resources allocation, it is often caught in the conflict of whether to give priority to the pursuit of socioeconomic benefits, to protect the ecological environment or to meet the relative fairness between regions.

In order to solve the above problems, this study clarified the accurate connotation of spatial equilibrium, proposing and interpreting the conept of spatial equilibrium of water resources composite system in system-region two stages for the first time, and proposed a set of dynamic quantification methods of spatial equilibrium corresponding to the above two nesting stages of system-region innovatively. Taking Lianshui Basin as an example, this paper comprehensively evaluated the dynamic evolution of the spatial equilibrium degree of water resources in the system-region two stages model. Firstly, a coupling coordination dynamic quantization model based on the comprehensive evaluation index of water resources, social economy and ecological environment was constructed to dynamically analyze the spatial and temporal evolution of the coupling coordination degree among the three subsystems within each region. Secondly, Thiel index was introduced to quantify the difference in coupling coordination degree among regions, so as to measure the degree of spatial equilibrium among regions and analyze its dynamic evolution characteristics. Thiel index of overall difference was further decomposed into inter-regional difference and difference within the region, and their respective contribution rate were calculated, so as to reveal the main sources of the imbalance.

2. Overview of the study area

Lianshui is located in the central part of Hunan Province and is a first-class tributary of the left bank of downstream of the Xiangjiang River. Lianshui flows from southwest to northeast through Lianyuan, Louxing, Xiangxiang, Xiangtan and other districts, then finally flows into the Xiangjiang River. The inter-annual and intra-annual distribution of precipitation in Lianshui Basin is extremely uneven, and the rainfall from April to September, the flood season, accounts for about 60% of the whole year. The average annual runoff in the basin is 4.199 billion m^3. The runoff depth gradually increases from 800 mm in the southeast to more than 1600 mm in the northwest mountainous area. The annual runoff variation coefficient Cv value is generally 0.29–0.38.

The per capita water resources in Lianshui Basin are only 1064 m^3, less than half of the per capita value of Hunan Province. The development and utilization rate of water resources is close to 45%, exceeding the internationally recognized warning line (40%). Lianshui Basin involves two key areas—the upstream Heng-Shao-Lou arid corridor and the downstream Chang-Zhu-Tan urban agglomeration: On the one hand, Heng-Shao-Lou arid corridor has a large shortage of water for agriculture, with an agricultural water shortage rate of more than 10%. Loudi, which is located in the arid corridor, has insufficient water resources conditions, serious regional water shortages, and water shortages for urban and rural living. There exist many problems in the development and utilization of water resources in Loudi such as more population but less water, more inferior water but less high-quality water, more in the west and less in the east, and more water resources in sparsely populated areas. On the other hand, with the in-depth implementation of the integration of Chang-Zhu-Tan urban agglomeration, industries and population have further gathered in this area, contributing nearly 50% of the province's GDP. This also leads that the local development and utilization rate of water resources has exceeded the warning line. Xiangtan, which is located in the Chang-Zhu-Tan urban agglomeration, is experiencing an aggravating trend of water resources overload.

This article takes 8 major districts in Lianshui Basin as examples, involving Loudi (four subordinate districts: Louxing, Shuangfeng, Lianyuan, Lengshuijiang), Xiangtan (four subordinate districts: Yuhu, Xiangtan, Xiangxiang, Shaoshan). The administrative divisions and distribution of water systems in Lianshui Basin are shown in Fig. 1.

3. Research methods

3.1. Theoretical framework

Two major modules, the conceptual interpretation and the dynamic quantitative model of spatial equilibrium, constitute the main theoretical framework of this paper, both of which can be divided vertically into two stages: system and region. Based on the background and definition of spatial equilibrium presented above, this study further explored the accurate connotation and quantitative evaluation methods of spatial equilibrium of water resources. This paper proposed that the spatial equilibrium of water resources composite system should be measured from the system-region two stages. The first stage is to ensure the coordinated development of the water resources composite system within each region. Water resources composite system is short for water resources - social economy - ecological environment composite system. From the perspective of system theory, the three subsystems of water resources, social economy and ecological environment are coupled to form the water resources composite system (Zhang & Wang, 2015). These three subsystems have their own characteristics, functions and operation rules respectively, but also exist mutual constraints, promotion and cooperation. Therefore, in the process of water resources development and utilization, it is necessary to pursue coordinated development among these three subsystems, so as to maintain the stability of the large composite system of water resources and to maximize the overall benefits of the composite system. The second stage is to pursue balanced development among all regions and promote equitable and coordinated regional development. Considering the space composed of different sub-regions as a whole, there are also relationships of mutual constraints, promotion and cooperation among different sub-regions. In the case of a certain total amount of water resources, there is a contradictory relationship in the allocation of water resources among different sub-regions. Therefore, it is necessary to pursue the coordinated development among different sub-regions so as to maintain the stability of the overall space.

Based on the above theory, this paper proposed a dynamic quantitative evaluation model of spatial equilibrium in system-region two stages, corresponding to the accurate connotation of spatial equilibrium in system-region two stages, which can be used to quantitatively analyze the dynamic evolution of spatial equilibrium of water resources composite system from the perspectives of system and region (Fig. 2).

3.2. Dynamic model in system-region two stages

The quantization model for the dynamic evolution of the degree of spatial equilibrium in system-region two stages is divided into two stages: (a) dynamic quantification of the degree of coordinated development among the three subsystems of water resources, social economy and ecological environment, (b) dynamic quantification of the degree of equilibrium development among regions. In the first stage, the comprehensive level of three subsystems is evaluated separately, and the quantization model for dynamic coupling coordination degree of the composite system is constructed by compounding the coupling degree, which reflects the degree of interaction and interdependence among three subsystems, and the comprehensive evaluation index, which reflects the development level of each systems (Roozbahani et al., 2015). The larger the D is, that is, the larger the result of the coupling coordination degree is, the more orderly and harmonious the development of the composite system tends to be, and the higher the degree of spatial equilibrium among systems is. In the second stage, the degree of spatial equilibrium among regions is quantified by the dynamic Theil index (Caizhi et al., 2010; Anwar and Ul Haq, 2013), which is reflecting the difference in the coupling coordination degree of each district. The larger the result is, the greater the difference in the coupling

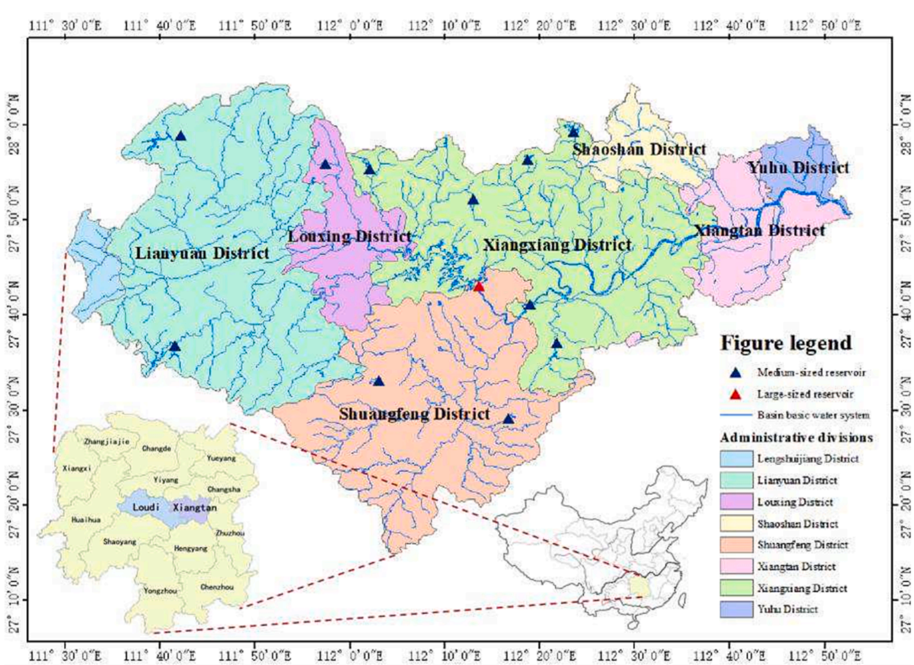


Fig. 1. Distribution map of administrative divisions and water systems in Lianshui Basin.

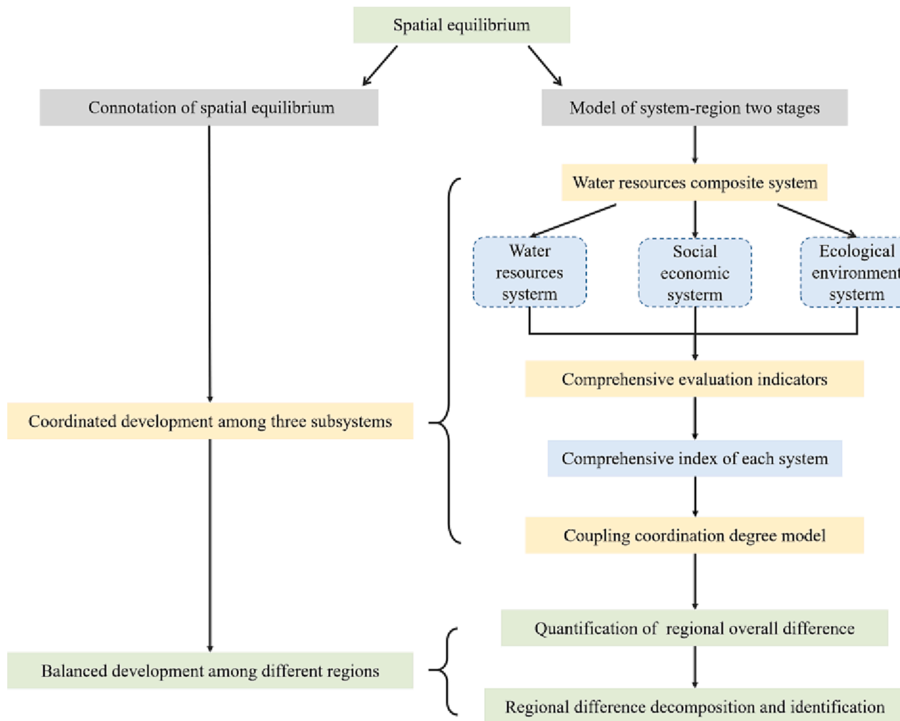


Fig. 2. Theoretical framework.

coordination degree is, and the lower the degree of spatial equilibrium among regions. The smaller the Th is, the lower the spatial difference of coupling coordination degree is, and the higher the degree of spatial equilibrium among regions is. The expression of the dynamic quantization modle of spatial equilibrium degree of system-region two stages is as follows:

$$D_{ik} = \sqrt{3 \times \left[\frac{UI_{ik} \cdot WI_{ik} \cdot EI_{ik}}{(UI_{ik} + WI_{ik} + EI_{ik})^3}\right]^{\frac{1}{3}} \times (\beta \times UI_{ik} + \gamma \times WI_{ik} + \delta \times EI_{ik})} \quad (1)$$

$$Th_i = T_{bri} + T_{wri} \quad (2)$$

In the formula: i represents the year. $k = 1,2 \dots \dots .0.8$, respectively indicates 8 districts in the study area. D_{ik} is the coupling coordination degree of k-district in the i-th year. WI_{ik} is the comprehensive evaluation index of water resources of k-district in the i-th year, reflecting the integrated level of water resources development and utilization. UI_{ik} is the comprehensive evaluation index of social economy of k-district in the i-th year, reflecting the level of socio-economic development. EI_{ik} is the comprehensive evaluation index of ecological environment of k-district in the i-th year, reflecting the level of ecological protection, and the specific calculation process is shown in 3.2.3. β、γ、δ is the weight index of three subsystems, this paper takes $\beta = 0.3, \gamma = 0.4, \delta = 0.3$. Th_i is the Theil index of the overall difference of coupling coordination degree among the regions in the whole basin in the i-th year. The Theil index of the overall difference can be further decomposed into inter-group difference and intra-group difference. T_{bri} is the inter-group difference between different prefecture-level cities in Lianshui basin in the i-th year. T_{wri} is the intra-group difference within a prefecture-level city in Lianshui basin in the i-th year, and the specific calculation process is shown in 3.3.

3.3. Comprehensive evaluation index

3.3.1. Indicators of water resources composite system

Due to the complex coupling relationship between the three subsystems of water resources, social economy and ecological environment (Di et al., 2022), it is necessary to select appropriate indicators to measure the development level of the three subsystems (Xu et al., 2020a, 2020b, 2020c; Jia et al., 2018). Following the selection principles of comprehensiveness, dynamics, scientificity and availability, the index system was divided into target layers, criterion layers and indicator layers according to the research purpose and research objects. This paper referred to the index selection in several works of literature (Xu et al., 2020a, 2020b, 2020c; Tao et al., 2022; Cheng et al., 2018), combining with the actual situation of the research area and the available data, the indicator system was preliminarily established consisting of 25 indicators. Correlation analysis is adopted to screen the preliminarily established indicator system. Indicators with a high degree of correlation have been deleted to reduce the overlap of information, so as to ensure the feasibility and rationality of the indicator system. Finally, a comprehensive evaluation index system of water resources, social economy and ecological environment in the basin was constructed, as shown in Table 1, which was composed of 3 target layers, 7 criteria layers and 22 indicators (Table 1).

3.3.2. Entropy- AHP combination weighting method based on minimum Euclidean space distance

Water resources, social economy and ecological environment constitute a composite large system with uncertainty and ambiguity. In order to absorb the advantages of different evaluation methods, this paper used the entropy weight method and AHP (analytic hierarchy process) to obtain two sets of weight for each system and integrated the weights of two single evaluation methods to obtain subjective–objective combination weighing results. The integration method to combine the weight of entropy and AHP was chosen based on the minimum Euclidean spatial distance (Ngo et al., 2012). The final results obtained by this method can “take care” of the results of both entropy method and AHP to the greatest extent and increase the reasonableness and accuracy of the evaluation results. The optimization model used for centralization is as follows:

Table 1
Indicators of water resources composite system.

Target layer	Criterion layer	Indicator layer	Unit	Indicator polarity
Comprehensive level of water resources development and utilization	Water resources endowment	Amount of water resources	Billion m^3	+
		Per capita water resources	m^3/poerson	+
		Annual precipitation	mm	+
	Water resources utilization structure	Primary industrial water use ratio	%	+
		Secondary industrial water use ratio	%	+
		Tertiary industrial water use ratio	%	+
	water resources development and utilization efficiency	Per capita domestic water	m^3	–
		Water consumption of 10 thousand RMB GDP	m^3/Million yuan	–
		Water consumption of 10 thousand RMB industrial added value	m^3/Million yuan	–
		Irrigation water consumption per mu	m^3/acres	–
Comprehensive level of socio-economic development	Economy	GDP per capita	yuan	+
		GDP growth rate	%	+
		Primary industrial GDP ratio	%	+
		Secondary industrial GDP ratio	%	+
		Tertiary industrial GDP ratio	%	+
	Society	Population	person	+
		Population density	person/km^2	–
		Urbanization rate	%	+
Comprehensive level of ecological and environmental protection	Ecological water	Ecological water consumption	Million m^3	+
		Percentage of ecological water consumption	%	+
	Discharge and treatment of wastewater	Total wastewater discharge	Million m^3	–
		Urban wastewater treatment rate	%	+

$$minf(\alpha_k)=\sqrt{\sum_{i=1}^{n}\left(\sum_{j=1}^{m}z_{ijk}\alpha_{1jk}-\sum_{j=1}^{m}z_{ijk}\alpha_{jk}\right)^2}+\sqrt{\sum_{i=1}^{n}\left(\sum_{j=1}^{m}z_{ijk}\alpha_{2j}-\sum_{j=1}^{m}z_{ijk}\alpha_{jk}\right)^2} \tag{3}$$

$$s.t.\begin{cases}\sum_{j=1}^{m}\alpha_{jk}=1\\ min(\alpha_{1jk},\alpha_{2j})\leq\alpha_{jk}\leq max(\alpha_{1jk},\alpha_{2j})\\ \alpha_{jk}\geq 0\\ j=1,2,\cdots,m\end{cases} \tag{4}$$

In the formula: m is the number of evaluation indicators. n is the number of years. $k = 1,2$ ....0.8, respectively indicates 8 districts in the study area. z_{ijk} are the elements of the normalized matrix, transformed from the original data by polarization, representing the value of the j-th indicator in k-district in i-th year. $\alpha_{1k} = (\alpha_{11k}, \alpha_{12k}, \cdots\alpha_{1mk})$ is the weight of k-district obtained by the entropy weight method (Xu et al., 2020a, 2020b, 2020c).$\alpha_2 = (\alpha_{21}, \alpha_{22}, \cdots\alpha_{2m})$ is the weight obtained by the AHP (Lee, 2015). α_{jk} is the final weight result of the j-th indicator in k-district. $\alpha_k = (\alpha_{1k}, \alpha_{2k}, \cdots\alpha_{mk})$ is the final weight obtained by entropy weight-AHP combination weighting method.

3.3.3. Comprehensive evaluation index

Using the above final weight results to calculate the comprehensive evaluation index of water resources, social economy and ecological environment, the calculation formula is as followed:

$$WI_{ik}=\sum_{j=1}^{m_1}\alpha_{jk}Z_{ijk} \tag{5}$$

$$UI_{ik}=\sum_{j=1}^{m_2}\alpha_{jk}Z_{ijk} \tag{6}$$

$$EI_{ik}=\sum_{j=1}^{m_3}\alpha_{jk}Z_{ijk} \tag{7}$$

In the formula: m_1, m_2, m_3 are the number of indicators of the corresponding system.

3.4. Pearson correlation analysis

The correlation between the comprehensive development level of water resources, social economy and ecological environment subsystems and the coupling coordination degree were analyzed, and the Pearson correlation coefficient is expressed as followed:

$$Correl(X,Y)=\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{8}$$

In the formula: *Correl* is the correlation coefficient, X and Y are two variables, x and y are the sample sequences of two groups respectively, and $\bar{x}$ and $\bar{y}$ are the mean values of the two groups of sequences respectively. At the significance level, the closer the absolute value of *Correl* is to 1, the stronger the correlation between the two variables is.

3.5. Regional difference decomposition and identification

The second stage of the quantization model for dynamic evolution of spatial equilibrium degree used Theil index of the overall difference in the coupling coordination degree between regions to quantify the spatial equilibrium degree of water resources at the regional level. Thiel index can further decompose overall difference into inter-group differences and intra-group differences so that it is often used to discern the main sources of variation (Malakar et al. 2018). The formula for Theil index of inter-group differences and inter-group differences are as follows:

$$T_{br}=\sum_{x=1}^{X}\left(\frac{D_x}{D}\right)\times\ln\left(\frac{D_x/D}{y_x/Y}\right) \tag{9}$$

$$T_{wr}=\sum_{x}^{X}\sum_{y}^{Y}\left(\frac{D_x}{D}\right)\times\left(\frac{D_{xy}}{D}\right)\times\log\left(\frac{D_{xy}/D}{1/y_x}\right) \tag{10}$$

In the formula: T_{br} is Theil index of inter-group difference. T_{wr} is Theil index of intra-group difference. X is the number of prefecture-level cities in Lianshui Basin (In this paper $X = 2$, respectively representing Loudi and Xiangtan). Y is the total number of districts in Lianshui basin (In this paper $Y = 8$). y_x means the number of districts in $\times$ prefecture-level city. D_x means the sum of the coupling coordination degree of all districts in $\times$ prefecture-level city. D_{xy} means the coupling coordination degree of y

district which is in × prefecture-level city. D means the sum of the coupling coordination degree of all districts.

In order to investigate the magnitude of the contribution of inter-group difference and intra-group difference to the overall difference in the coupling coordination degree and to identify the main source of spatial imbalance in coupling coordination, the contribution rates of inter-group difference and intra-group difference were used to measure (Cui et al. 2022). The calculation formula is as followed:

$$contribution\ rates\ of\ inter-group\ differences = \frac{T_{br}}{Th} \tag{11}$$

$$contribution\ rates\ of\ intra-group\ differences = \frac{T_{wr}}{Th} \tag{12}$$

4. Results and discussion

4.1. Dynamic evolution of water resources development and utilization

The comprehensive evaluation index of water resources (*WI*), social economy (*UI*) and ecological environment (*UI*) in Lianshui Basin from 2011 to 2019 were calculated (Fig. 3).

Both *WI* and *UI* showed an overall upward trend from 2011 to 2019. *WI* fluctuated greatly from year to year and was easily influenced by the water inflow condition in that year: 2011 was an especially low flow year, and *WI* was at a poor level in the whole basin; 2012 was a low flow year, but due to the extremely uneven spatial distribution of water resources in that year, the dry situation in upstream was more serious than in downstream, so *WI* in the upper reaches dropped more significantly. Furthermore, 2018 was also an especially low flow year, but *WI* in all districts has improved significantly compared to 2011, with an average increase of 116.90% compared with 2011 and an average annual growth of 10.16%, which indicated that the level of water resources development and utilization in Lianshui Basin has been improved and the ability to cope with conditions such as drought and water shortage has been enhanced in the same unsatisfactory water conditions.

In terms of ecological environment, *EI* of Xiangtan showed an increasing trend. *EI* of Loudi had no obvious trend, but was greatly improved around 2019. *EI* of Loudi was significantly lower than that of Xiangtan before 2018, which was probably due to the fact that Loudi, located in the arid corridor, was still facing the problem of regional water shortage, and the water for production and living has seriously occupied the ecological water. Therefore, the region should focus on improving the level of water resources development and utilization in the future, and strengthening the construction of projects for water diversion and transfer.

4.2. Dynamic evolution of spatial equilibrium among systems

Based on the calculation results of the coupling coordination degree of eight districts from 2011 to 2019, the spatial and temporal dynamic evolution of the coordinated development degree of the composite system of water resources-society and economy-ecological environment in Lianshui Basin was analyzed to reveal the current situation and trend of the spatial equilibrium degree among three systems.

4.2.1. Temporal dynamic evolution of the coupling coordination degree

The degree of coordinated development among three subsystems within each district was reflected by the coupling coordination degree (Fig. 4). From 2011 to 2019, the coupling coordination degree of all districts fluctuated slightly but showed a relatively stable upward trend overall, which showed that the coordinated development of the composite system in Lianshui Basin has been improving, and the spatial

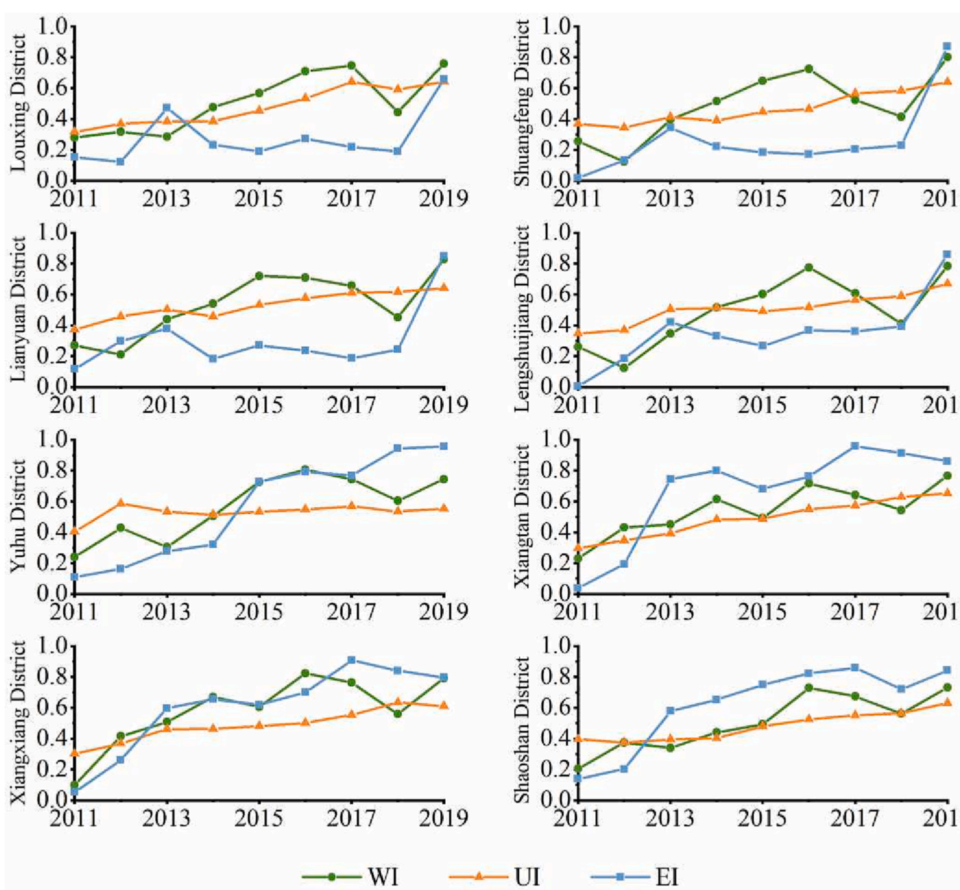


Fig. 3. WI, UI and EI of 8 districts in Lianshui Basin from 2011 to 2019.

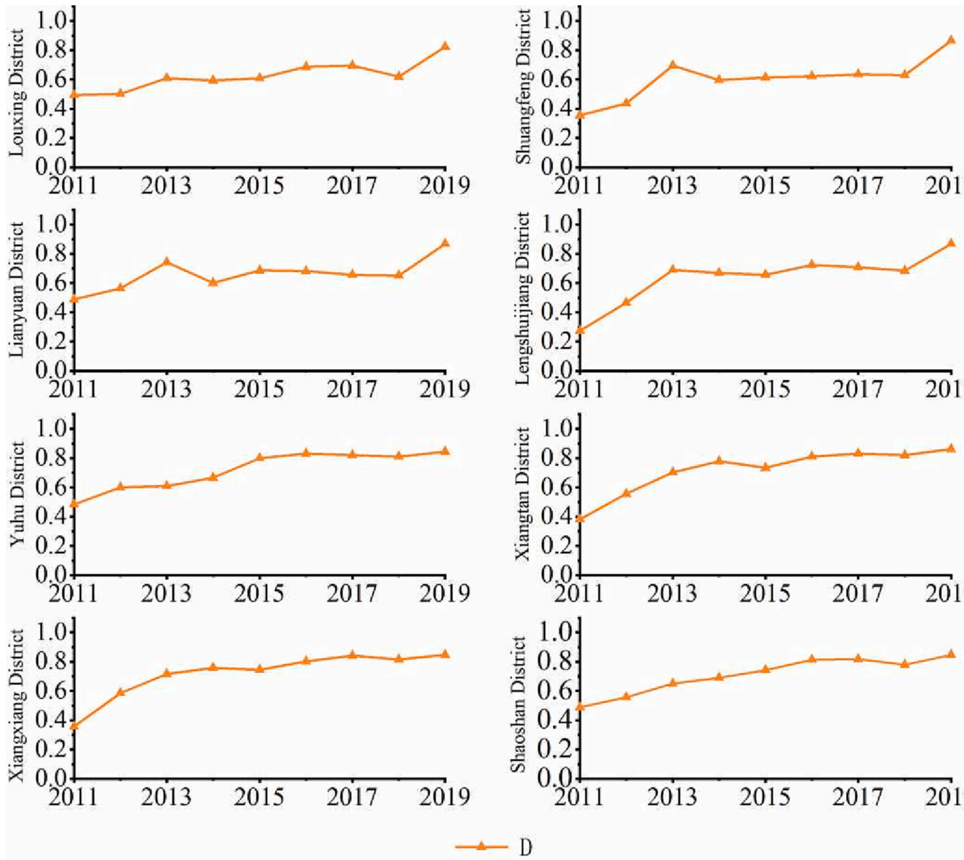


Fig. 4. Temporal dynamic evolution of coupling coordination degree in 8 districts in Lianshui Basin from 2011 to 2019.

equilibrium among systems has gradually increased. The average value of the basin-wide coupling coordination degree increased by 3.51 cumulatively from 2011 to 2019 and increased by 105.74% in 2019 compared with 2011, with an average annual increase of 9.44%. The most significant increase in coupling coordination degree between 2011 and 2019 was in Lengshuijiang, with a cumulative increase of 0.51 and an average annual increase of 15.53%. The average value of the basin-wide coupling coordination degree increased by 1.24 cumulatively from 2015 to 2019 and increased by 22.12% in 2019 compared with 2015, with an average annual increase of 5.12%. The most significant increase from 2015 to 2019 was in Shuangfeng, with a cumulative increase of 0.25 and an average annual increase of 8.97%. It can be seen that the rate of improvement of the basin-wide coupling coordination degree was gradually slowing down, and there were small fluctuations in some areas in some years, but the overall positive trend was relatively stable.

In addition, comparing *D* and *WI* year by year, it can be found that the magnitude of coupling coordination degree among systems was directly related to the level of the comprehensive evaluation index of water resources in that year. For example, the water inflow conditions in 2011, 2012 and 2018 were poor, so the comprehensive evaluation indices of water resources were low, which in turn led to a poor level or a decrease of coupling coordination in all regions. This indicates that there is a correlation between the degree of coordinated development of the whole composite system and the condition of the subsystem itself, and that improving the development level and stability of the subsystem is also conducive to the balanced and coordinated development of the whole system (Fang et al. 2017).

4.2.2. Spatial dynamic evolution of the coupling coordination degree

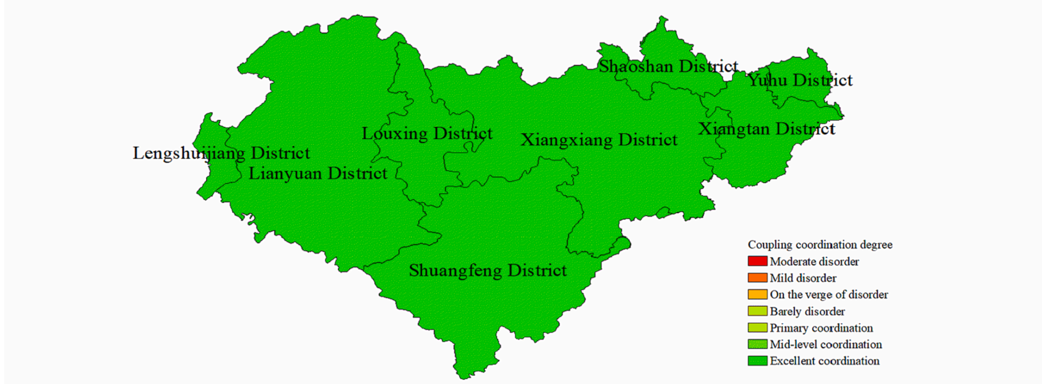
Based on the coupling coordination degree from 2011 to 2019, the degree of coupling coordination development of the composite system of each district was ranked in this paper (Ma et al., 2020). Three time-cross-sections 2011, 2015, and 2019, were selected for display and analysis (Fig. 5). In 2011, the coupling coordination level of each region was relatively poor, among which Lengshuijiang was in moderate disorder, Shuangfeng, Xiangtan and Xiangxiang were in mild disorder, and the remaining four districts were on the verge of disorder. The coupling coordination level of each region has been greatly improved in 2015, Yuhu has been the first to reach good coordination, the remaining three districts in Xiangtan were all intermediate coordination, and all four districts in Loudi were primary coordination. All eight districts in the basin have reached good coordination in 2019. It can also be seen that the degree of coordinated development in Xiangtan was slightly better than that in Loudi before 2019, but in 2019 the two cities have reached a comparable level. Overall, the coupling coordination degree among systems in each districts of Lianshui basin has been greatly improved, and the development level of good coordination has been reached in the whole basin. In the future, each district still needs to formulate corresponding comprehensive development strategies according to its own actual situation to promote the development of the three subsystems toward high-quality coordination.

4.3. Correlation analysis

The correlation analysis between the comprehensive development level of the three subsystems (*WI*/*UI*/*EI*) and the coupling coordination degree (*D*) was carried out respectively. The results showed that *UI*/*EI* showed strong positive correlation ($0.6 \leq correl < 0.8$) with *D*, while *WI* and *D* showed very strong correlation ($correl = 0.833$). On this basis, the correlation between *WI* and *D* was analyzed year by year. The results shew that *WI* and *D* showed a strong correlation in the years when the comprehensive evaluation index of water resources was low, indicating that the poor development level of water resources subsystem would

(a) Spatial dynamic evolution of coupling coordination degree of eight districts in Lianshui Basin in 2011

(b) Spatial dynamic evolution of coupling coordination degree of eight districts in Lianshui Basin in 2015



(c) Spatial dynamic evolution of coupling coordination degree of eight districts in Lianshui Basin in 2019

Fig. 5. Spatial dynamic evolution of coupling coordination degree of eight districts in Lianshui Basin in 2011, 2015 and 2019.

greatly affect the coupling coordination degree of the whole composite system.

4.4. Dynamic evolution of spatial equilibrium among regions

4.4.1. Regional overall difference

According to the results of the coupling coordination degree of eight districts in Lianshui basin from 2011 to 2019, the overall difference Theil index was calculated (Fig. 6). The overall difference of 2011, 2013 and 2019 were significantly smaller than other years, which was somehow related to the more even distribution of water resources in these years. The values of Theil's index in the remaining years were all within a small range of variation, and the overall difference have not improved consistently and stably, which indicated that the spatial equilibrium between regions still needs to be further improved.

4.4.2. Main source of difference and corresponding contribution rates

The contribution of inter-regional difference and difference within the region to Theil index of the overall difference from 2011 to 2019 was calculated and showed in different colors (Fig. 6). Difference within the region were greater than inter-regional difference for all nine years, and became the main source of overall difference. This phenomenon was particularly evident in 2011, 2013 and 2019. This illustrated that within each prefecture-level city, the problem of unbalanced development between regions was more serious, which requires an overall control of the actual situation of each region according to local conditions, to give full play to the advantages of each region and make up for the shortcomings. For areas with developed social economies, the level of development and utilization of water resources and the awareness of ecological and environmental protection need to be improved simultaneously. And for the regions with abundant water resources, it is also necessary to make full use of this valuable resource and develop and utilize it reasonably

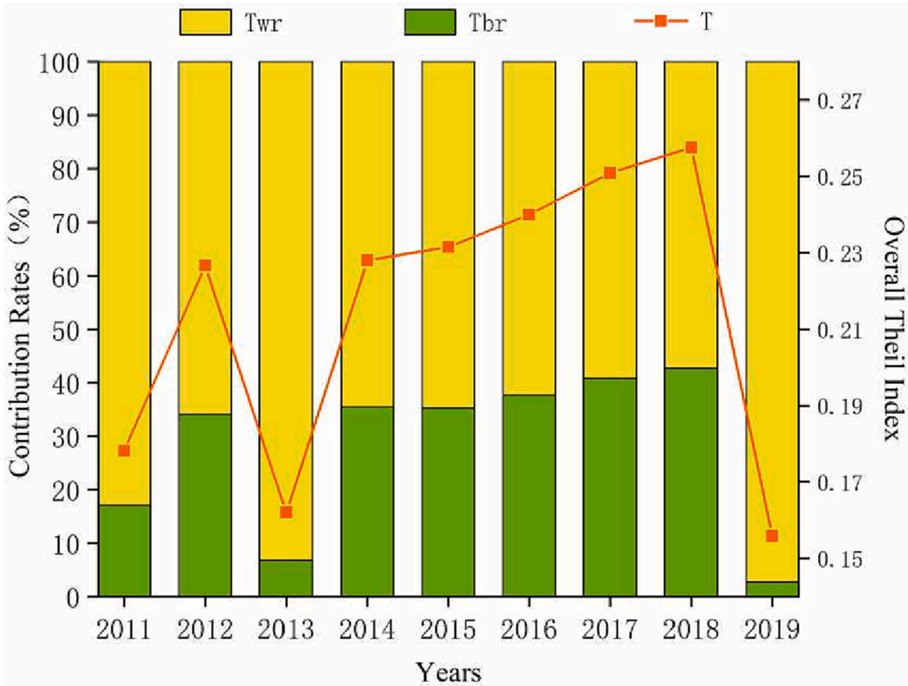


Fig. 6. Theil index of the overall difference and the contribution rates of inter-regional difference and difference within the region from 2011 to 2019.

under the premise of safeguarding the ecological environment, so as to give full play to its due economic benefits.

5. Breakthroughs and limitations

Compared with previous studies that only discussed the coordinated development degree of water resources and other subsystems in a certain region or the balanced development degree among different regions, we proposed a comprehensive accurate definition and a refined dynamic quantification model of spatial equilibrium in system-region two stages in an original way, which can evaluate and analyze the dynamic evolution of the spatial equilibrium more comprehensively and accurately. This study broke through the limitation in previous methods that the evaluation dimension was relatively single. We not only analyzed the coupling coordination degree among various systems, but also further studied the regional difference of the coupling coordination degree to quantify the degree of spatial equilibrium among regions. In an innovative way, the two frameworks were nested together as a dynamic evaluation structure of spatial equilibrium, which makes the quantification of spatial equilibrium more elaborative and effective. The dynamic quantitative model proposed in this paper can be used as a general means and practical tool for spatial equilibrium evaluation, and is applicable to various situations in various systems, various regions, various scales and various time spans, which have practical value and prospects for promotion in the future.

At the same time, there are still some limitations and deficiencies in this study, which need to be further studied and improved. Due to the lack of data, this paper is limited in the construction of the indicator system, and the time series need to be further extended, so as to better reflect the evolution trend of the development level of each subsystem and spatial equilibrium degree. In the future, more comprehensive indicators can be included, and the research period or research area can be expanded. Quantitative evaluation of spatial equilibrium under various time spans and spatial scales can be widely realized, and a unified evaluation system and evaluation standard can be formed.

6. Conclusions

In this study, two stages of spatial equilibrium, namely spatial equilibrium among systems and spatial equilibrium among regions were defined, which completed and enriched the connotation of spatial equilibrium. A refined dynamic quantitative evaluation model of spatial equilibrium in system-region two stages was proposed as well. We analyzed the spatio-temporal dynamic evolution of the development level of each subsystem, the coordinated development degree of three subsystems, and the spatial equilibrium degree in Lianshui Basin. The main results are as follows:

(i) Water resources and ecological environment systems are vulnerable to the influence of incoming water conditions. Therefore, water resources should be rationally developed and utilized, and engineering measures such as construction of reservoirs and dams should be taken to enhance the stability of systems.
(ii) The spatial equilibrium in the "system stage" has been improved year by year, and the whole basin has reached a good coordination level by 2019. However, there is still room for improvement in the distance from high-quality coordination, so the focus should be on the weaker systems to enhance the shortcomings and weaknesses.
(iii) The spatial equilibrium in the "region stage" has not been significantly improved. In addition, the difference within the region is the main source of regional difference. In the future, it is necessary to strengthen the balanced and coordinated development among regions, enhance the interconnection of water resources, and improve the spatial connectivity pattern of water resources.

This study provided dynamic evolution results of the spatial equilibrium, and can serve as a guide for the rational development and utilization of water resources in the future. Furthermore, the accurate connotation and dynamic quantitative refinement model proposed in this paper are of great theoretical and practical significance for evaluating the degree of spatial equilibrium of water resources composite system.

CRediT authorship contribution statement

Ziqin Zheng: Conceptualization, Methodology, Software, Writing – original draft, Formal analysis, Writing – review & editing. **Zengchuan Dong:** Project administration, Supervision. **Wenzhuo Wang:** Project administration, Supervision. **Yalei Han:** Data curation, Methodology. **Can Cui:** Resources, Visualization. **Xinkui Wang:** Validation. **Yiqing Shao:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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