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Spatial Equilibrium Evaluation of the Water Resources in Tai'an City Based on the Lorenz Curve and Correlation Number

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Abstract: Water resource spatial equilibrium evaluations provide the bases for water resource utilization and allocation. To analyze the regional spatial water resource matching balance, this study constructed a water resource spatial matching model based on the Gini coefficient and Lorenz curve methods. To further reflect the influence of each subregion on the whole region, we combined the correlation number and Gini coefficient methods to propose the water resource spatial balance evaluation method. Herein, we constructed nine Lorenz curve pairs that matched the total water resources and total water use with cultivated land area, population, GDP (Gross Domestic Product) of the secondary industry, GDP (Gross Domestic Product) of the tertiary industry, and agricultural irrigation water consumption. Set pair analysis theory was applied to calculate sample correlation numbers and determine equilibrium levels, which were then compared to Gini coefficient method-based results for Tai'an city evaluation. The results showed that the total water consumption spatial equilibrium in Tai'an city from 2011 to 2020 was favorable, while the total water resource results for Tai'an city greatly differed, especially the balance between total water resources and GDPs of the secondary and tertiary industries, which should be further improved. In practice, quantitative analysis of the water resource spatial equilibrium state in Tai'an city is important for efficient water resource utilization and coordinated development of water resources and economic and social environments.

Keywords: Gini coefficient; Lorenz curve; number of connections; spatial equilibrium of water resources

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1. Introduction

The uneven distribution of water resources in time and space and the contradiction between population and economy are common global development problems at present, especially in China. Water resource systems constitute the basic controlling factor of social and economic development and are key to connecting water supply security, food production security, energy development, and ecological protection [1]. In recent years, rapid economic and social development in some regions has increased the demand for water resource utilization and allocation, among which the spatial-temporal characteristics of regional water resources are the primary prerequisites for water resource utilization and allocation [2]. To better satisfy the balanced development of the regional economy and society, support the favorable function of ecological systems, and reduce the occurrence of water crises, scientific and reasonable allocation of water resources has remained the focus of attention among water resource scholars [3–6]. Research on the balanced prediction, evaluation, and optimal regulation of complex systems comprising population, natural resources, economy, and environment has become a challenging and frontier subject among hydrology researchers worldwide [7–10]. At present, China implements water resource management based on the concept of spatial balance. Based on the exploitability and utilization of water resources, China determines the structure and scale of economic and social development comprehensively and reasonably to ensure the bearing capacity of regional water resources and the water ecology and environment [11].

The study of water resource spatial equilibrium remains in the initial stage and mainly focuses on the development of regional water resource spatial equilibrium evaluation [12–15]. The main research method is to use Gini coefficient method and variable fuzzy set to quantify the balance of water resources utilization in each sub-region of the study area, and further build an evaluation model to evaluate the overall water resources balance of the study area. Xia et al. calculated and analyzed the balance of the water resource load index, water and soil resource matching coefficient, and water use benefits by using the Gini coefficient method and coordinated development degree method [16]. Yang et al. analyzed the dynamic changes in the spatial balance of water resources in the Yangtze River Economic Belt from 2009 to 2018 considering a fuzzy set of variables and the Gini coefficient coupling method [17]. Research on water resource spatial equilibrium involves relatively complex topics, including the interactions within and between multiple systems. Yang constructed a new water resource spatial equilibrium evaluation model based on the variable set principle and the partial relation number method, and the eigenvalue and grading strategy were integrated for water resource spatial equilibrium evaluation [18]. Liang et al. used the Dagum Gini coefficient and kernel density estimation methods to study the evolution trend of the water resources in Gansu Province from 2010 to 2018 [19]. Liu et al. introduced the Gini coefficient and location quotient methods, which provides a reference for the optimization of water resource utilization in Gansu Province [20]. Wang et al. used the Gini coefficient method, water political events, and social network analysis to assess the matching degree between water and socioeconomic elements and analyze the dynamics of water politics in transboundary river basins in Central Asia (CA) [21]; moreover, Correa-Parra et al. used the Gini coefficient method to comprehensively analyze Chilean water market inequality [22]. Zhou et al. used the Dagum Gini coefficient and SPA methods to evaluate the difference in the water resources carrying capacity in Anhui Province [23]. N. K. Gunasekara et al. estimated the risk of international water conflicts by the Gini coefficient method, which could help to estimate the risk of water resource conflicts in the context of climate change [24]. Kazama et al. used the Lorenz curve and Gini coefficient methods to quantify the unbalanced distribution of water resources in the Mekong River basin and other parts of Thailand [25]. Masaki Y. et al. evaluated the imbalance of the seasonal water resource distribution in major global rivers by the Gini coefficient and Lorenz curve methods [26]. Kazemi M. et al. proposed a multiobjective optimization model for water resource allocation based on the Lorenz curve and Gini coefficient methods to evaluate the current and future equilibrium states of water resource allocation in the Seferdrud Basin, Iran [27]. Zhang et al. used an improved SPA model to evaluate water resource assets in Wuhan using Maslow's hierarchy of needs theory and the Gini coefficient method [28]. Chen et al. established a water resource equilibrium regulation model from the demand side and applied it to the Yellow River Basin (YRB) to realize spatiotemporal equilibrium regulation of water resources [29].

To sum up, the research on the spatial equilibrium of water resources has attracted wide attention and become one of the prevalent issues in the field of water resources. However, most of them only analyzed the spatial equilibrium of the total water resources, relatively few analyzed the water consumption, and most of them only used a single method for analysis. In this study, the matching relationship between total water use, cultivated land area, population, and GDP of the secondary industry was increased, and the quantitative model was built by combining Gini coefficient and correlation number, which could more accurately and comprehensively evaluate the water use balance of Tai'an city. The total amount of water resources in Tai'an city is insufficient, and the spatial and temporal distributions are uneven. The obvious fluctuations in annual precipitation lead to drastic interannual changes in water resources, and their development and utilization are difficult. Therefore, the evaluation of the regional spatial water resource matching balance in Tai'an city is conducive to efficient utilization and reasonable allocation of water resources. Water replenishment and transfer based on research results and actual situation can avoid serious water shortages and waste of water resources in some areas and achieve dynamic balance between supply and demand of water resources at a higher level. It can also help formulate the urban planning and development ideas and water conservancy ecological construction pattern in line with Tai'an city, enhance the integrity and coordination of local water resources, and promote symbiosis between humans and nature. To fully reflect the influence of each subregion on the whole region during the evaluation, this study combined the correlation number and Gini coefficient, and proposed an evaluation method of water resources spatial balance combining the two. Firstly, the Gini coefficient was calculated to determine the spatial balance level of water resources in Tai'an city, and then a water resources spatial matching model based on the Gini coefficient and Lorenz curve was constructed. Nine pairs of Lorenz curves of the matching relationship between the total water resources and the total water use, arable land area, population, Gross Domestic Product (GDP) of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water consumption were constructed. Finally, SPA theory was applied to calculate the correlation number of the sample values and determine the equilibrium level, and a comparison was made to the Gini coefficient method. This study can provide a theoretical basis for realizing efficient water resource utilization in Tai'an city and promoting the coordinated development of water resources and the economic and social environments.

2. Methods and Model Building

2.1. Study Area

Tai'an city is located at the southern foot of Mount Tai in the middle of Shandong Province, between 116°02′ and 117°59′ east longitude and 35°38′ and 36°28′ north latitude. The city is 176.6 km long from east to west and 93.5 km wide from north to south. The total area of the city is 7762.0 km^2, accounting for 4.95% of the total area of the province. Tai'an has jurisdiction over 6 administrative regions: Taishan district, Daiyue district, Xintai city, Feicheng city, Ningyang county, and Dongping county. As shown in Figure 1, they are divided into the Yellow River and the Huaihe River basins. The basins are mainly the Dawen River system of the Yellow River basin in the north and the Sihe River system and Liangji Canal system of the Huaihe River basin in the south. The average annual precipitation of Tai'an city is 690.6 mm, which is characterized by drought in spring, flood in summer, and drought in late autumn. The annual precipitation is also more obvious, abundant, and dry alternately.

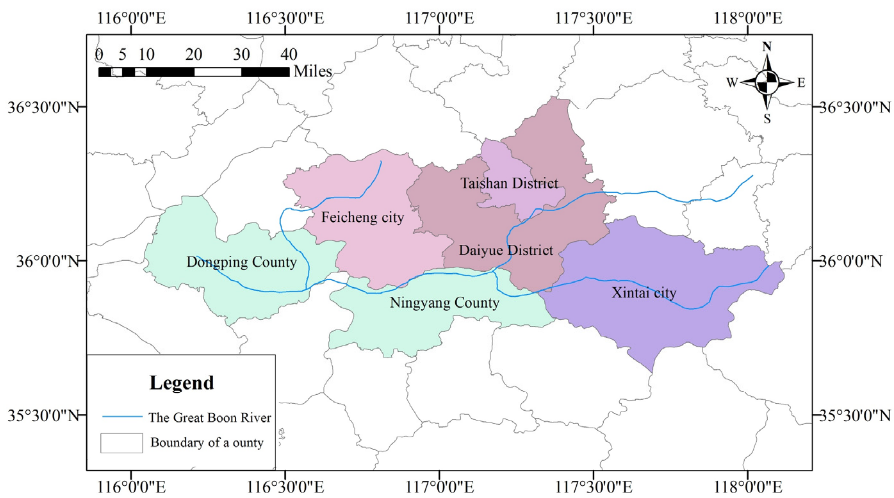

Figure 1. Geographical location and administrative division of Tai′an city.

2.2. Gini Coefficient Method

The Lorenz curve method has been widely used to compare and study the economic income equilibrium among people in countries or regions; the concept of the Gini coefficient was proposed based on the Lorenz curve [30]. The Gini coefficient can objectively and accurately evaluate the income gap of the sample economy, so the Gini coefficient was introduced to study the distribution equilibrium of specific factors in the field of water resources.

(1) The water resource factors include the regional water resources (y_1) and total water use (y_2), and the matching objects include the agricultural acreage (x_1), population (x_2), GDP of the secondary industry (x_3), GDP of the tertiary industry (x_4), and agricultural irrigation water consumption (x_5). Due to agricultural irrigation, water use is highly correlated with the total water resources, while the total water amount exhibits a less notable correlation. Hence, the matching relationships could be determined as y_1–x_1, y_1–x_2, y_1–x_3, y_1–x_4, y_1–x_5, y_2–x_1, y_2–x_2, y_2–x_3, and y_2–x_4.

In this paper, the Gini coefficient G of water resources and economic and social development factors was divided into nine types, as summarized in Table 1.

Table 1. Gini coefficient matching relationship between the water resource and matching factors.

Water Resource Factor	Matching Factor	Gini Coefficient Matching Relationship	
Water resources (w)	Agricultural acreage (1)	Water resources and cultivated land area	Gw1
	Population (2)	Water resources and population	Gw2
	GDP of the secondary industry (3)	Water resources and GDP of the secondary industry	Gw3
	GDP of the tertiary industry (4)	Water resources and GDP of the tertiary industry	Gw4
	Water consumption for agricultural irrigation (5)	Total water resources and agricultural irrigation water consumption	Gw5
Water use (u)	Agricultural acreage (1)	Water use and cultivated land area	Gu1
	Population (2)	Water use and population	Gu2
	GDP of the secondary industry (3)	Water use and GDP of the secondary industry	Gu3
	GDP of the tertiary industry (4)	Water use and GDP of the tertiary industry	Gu4

(2) The total amount of water resources and the total water consumption per unit of agricultural irrigation in each subregion were listed in ascending order: unit agricultural acreage, unit population, unit GDP of the secondary industry, unit GDP of the tertiary industry, and unit agricultural irrigation water consumption.

(3) The proportion of matching objects (x_1–x_5) in each subregion to those in the whole region was calculated.

(4) The matching primitives (y_1 and y_2) and matching objects (x_1–x_5) in each subregion were accumulated in proportion to the total region.

(5) The X-axis denotes the accumulative ratio of the matching objects (x_1–x_5) in each subregion to those in the whole region, and the Y-axis denotes the accumulative ratio of the matching primitives (y_1 and y_2) to draw the Lorenz curve, as shown in Figure 2. In this paper, the triangular area algorithm was used to calculate the Gini coefficient values of the water resource matching primitives and each matching object [31]:

$$G = \sum_{j=1}^{n-1} x_j y_{j+1} - x_{j+1} y_j, \tag{1}$$

where G is the Gini coefficient between the water resource and matching factors in the whole region; x_j denotes the unit agricultural acreage, unit population, unit GDP of the tertiary industry, unit GDP of the secondary industry, and unit agricultural irrigation water consumption in each subregion, the total water resources in water subdomain j, or the agricultural acreage, population, GDP of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water use in the whole region as a proportion of the total value; y_j is the accumulative value of the matching primitive proportion in subregion J; and n is the number of subregions.

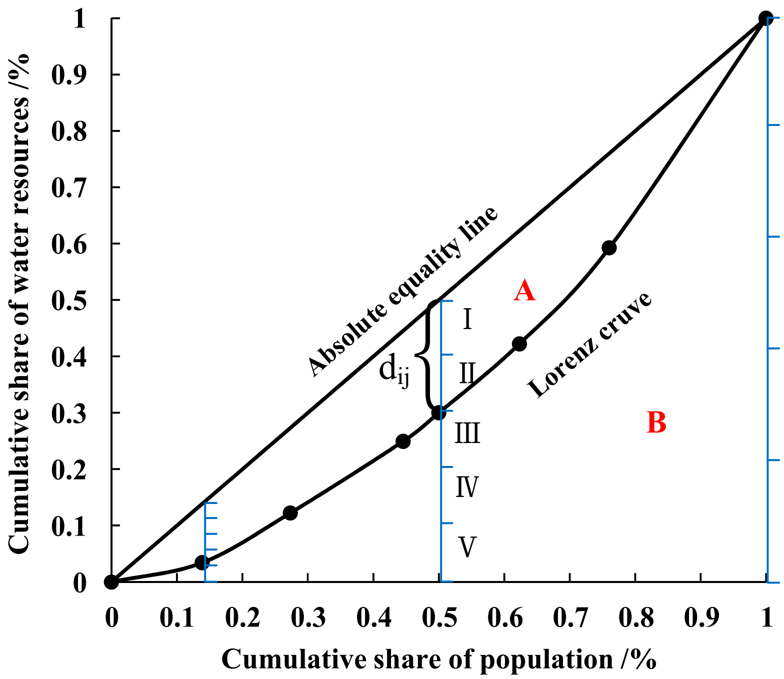

Figure 2. Diagram of the water resource spatial equilibrium evaluation model based on the connection number and Lorenz curve. (I–V indicates the level classification of evaluation indicators in the following paragraphs.)

The area between the Lorenz curve and the absolute equality line (45° line) is A, and the area enclosed by the Lorenz curve and the horizontal axis is B. A/(A + B) is the Gini coefficient [32], reflecting the magnitude of the difference between the two curves and the area enclosed by the horizontal axis. The Gini coefficient value generally ranges from 0 to 1. The lower the Gini coefficient value is, the more balanced the relationship. Conversely, the relationship is more unbalanced [33].

The corresponding relationship between the Gini coefficient and the evaluation results is provided in Table 2.

Table 2. Corresponding relationship of the Gini coefficient evaluation results.

Gini coefficient	Less than 0.2	0.2–0.3	0.3–0.4	0.4–0.5	Greater than 0.5
Evaluation results	Absolute balance	Comparative balance	Relative balance	Comparative inequality	Absolute inequality

2.3. Connection Number Method

The Lorenz curve and Gini coefficient methods capture the economic income equilibrium state of residents. By introducing these methods into the field of water resources, we can evaluate the overall equilibrium state of regional water resources and evaluate the equilibrium degree among subregions according to the Lorenz curve trend and data comparison. To reduce the difference resulting from the use of one method and enhance the credibility of the findings, the spatial equilibrium degree of regional water resources was evaluated in combination with the theoretical research method of the connection number.

SPA connects two related sets in the research problem to form a new deterministic and uncertain set pair system H and analyzes it from the three aspects of the identity degree, difference degree, and opposition degree to quantitatively describe the fuzzy relationship of the set pair system and comprehensively address uncertain problems [34,35]. The connection number is the mathematical expression of SPA, which can generally be obtained as:

$$u = a + bI + cJ, \tag{2}$$

where u is the relation number of H; a, b, and c are the identity degree, difference degree, and opposition degree, respectively, with $a + b + c = 1$; J is the coefficient of the opposition degree, with $J = -1$ generally denoting positive or negative opposition; and I is the coefficient of the difference degree, which can be determined based on J and generally occurs within the [−1, 1] range [36].

The connection number of the sample values of all matching relations was calculated. In this paper, the connection number u between water resources and the economic and social development factors was divided into nine types, as summarized in Table 3.

Table 3. Connection number matching relationship between the water resource and matching factors.

Water Resource Factor	Matching Factor	Connection Number Matching Relationship	
Water resources (w)	Agricultural acreage (1)	Water resources and cultivated land area	uw1
	Population (2)	Water resources and population	uw2
	GDP of the secondary industry (3)	Water resources and GDP of the secondary industry	uw3
	GDP of the tertiary industry (4)	Water resources and GDP of the tertiary industry	uw4
	Water consumption for agricultural irrigation (5)	Total water resources and agricultural irrigation water consumption	uw5
Water use (u)	Agricultural acreage (1)	Water use and cultivated land area	uu1
	Population (2)	Water use and population	uu2
	GDP of the secondary industry (3)	Connection number of water use and GDP of the secondary industry	uu3

SPA was used to calculate the five-element connection number u_{ij} between the sample value of each matching relationship d_{ij} and grade standard s_{ijk} [37], where i = 1, 2, 3, 4, 5 denotes the serial number of the matching relationship, j = 1, 2 . . . , n denotes the serial number of the subregion, and k = 1, 2, 3, 4, 5 is the rank.

$$u_{ij} = v_{ij1} + v_{ij2}I_1 + v_{ij3}I_2 + v_{ij4}I_3 + v_{ij5}J, \tag{3}$$

where v_{ij1}, v_{ij2}, v_{ij3}, v_{ij4}, and v_{ij5} are the identity degree, difference degree, and opposition degree components of the normalized five-member relationship number, and I_1, I_2, and I_3 are the coefficients of the difference degree, with a value of [−1, 1]. The calculation method has been reported elsewhere [38,39].

2.4. Construction of the Water Resource Spatial Equilibrium Evaluation Model

(1) Construction of the matching relationships. The interaction between the water resource system and economic and social system was comprehensively considered, and the matching relationship of the water resource quantity (y_1–x_1, y_1–x_2, y_1–x_3, y_1–x_4, y_1–x_5,

y_2–x_1, y_2–x_2, y_2–x_3, and y_2–x_4) was adopted as the evaluation index according to the principles of rationality, applicability, and operability [38]. A spatial equilibrium evaluation of the regional water resources was conducted.

(2) Calculation of the sample values d_{ij}. The longitudinal distance between any point on the Lorenz curve corresponding to $y = x$ (the absolute mean curve) and the same point on the abscissa can be expressed as d_{ij} (as shown in Figure 2), which can be calculated as:

$$d_{ij} = x_{ij} - y_{ij}, \tag{4}$$

where x_{ij} is the cumulative value of the proportion of matching object i in the whole region to that in subregion j; y_{ij} is the cumulative value of the proportion of the total water resources corresponding to matching object I in subregion j; i is the serial number of the matching relationship (i = 1, 2, 3, 4, and 5 denote the cultivated land area, population, GDP of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water consumption, respectively); and j is the serial number of the subregion (j = 1, 2, . . . , n).

(3) Classification of the evaluation indicators. The closer the Lorenz curve is to the absolute mean curve, the higher the equilibrium between the matching primitives and objects, and vice versa. The length of vertical line segment S between each point on the absolute mean curve and the horizontal axis was divided into five equal grades (I, II, III, IV, and V) as the grade standard s of d_{ij}, in which grade I is close to the absolute mean curve indicates equilibrium, grade V is far from the absolute mean curve indicates imbalance, etc.

(4) Calculation of the connection number of the matching relationship. With the use of the special value method [40], the coefficients of the difference degree (I_1 = 0.5, I_2 = 0, and I_3 = −0.5) and the coefficient of the opposition degree (J = −1) were considered to calculate the connection number of each matching relationship. The evaluation grades can be divided according to the standards listed in Table 4 by referring to the principle of Gini coefficient classification (60-point scale) and relevant trial results [41].

Table 4. Evaluation grade of the matching relationship between the Gini coefficient and connection number.

Gini coefficient	[0, 0.2)	[0.2, 0.3)	[0.3, 0.4)	[0.4, 0.5)	[0.5, 1.0)
Evaluation results	High match	Comparative match	Relative matching	Comparative mismatch	High mismatch
Connection number	[−1.00, −0.05]	(−0.05, 0.20]	(0.20, 0.38]	(0.38, 0.58]	(0.58, 1.00]
Evaluation results	V (disequilibrium)	IV (comparative disequilibrium)	III (critical)	II (comparative equilibrium)	I (equilibrium)

3. Results

Choosing Tai'an city as the research area, the total water resources and total water use in the six administrative regions of Tai'an city from 2011 to 2020 were selected as matching primitives. The agricultural acreage, population, GDP of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water consumption were selected as matching objects. Nine pairs of matching relationships were evaluated in regard to spatial equilibrium. The data mainly originated from the Tai'an Statistical Yearbook from 2012 to 2021 [42], Tai'an Water Resources Bulletin from 2011 to 2020 (from Tai'an Water Resources Bureau) [43], status quo change data of the land resources in Tai'an [44], and data of the administrative divisions [45]. According to the above evaluation steps of the water resource spatial equilibrium based on the connection number and Lorenz curve and equations, the association values and corresponding evaluation grades of the nine pairs of matching relationships in Tai'an city from 2011 to 2020 were calculated, and the corresponding Gini coefficient was obtained according to Equation (1) to evaluate the water resource spatial equilibrium for comparative analysis. The evaluation results for the Gini coefficient and correlation number of the total water resources and total water consumption in Tai'an city are shown in Tables 5 and 6, the evaluation criteria are shown in Figures 3 and 4, respectively.

Table 5. Gini coefficient evaluation results.

Gini Coefficients	Results of Gini Coefficient Evaluation in Different Years									
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Gw1	0.294	0.237	0.307	0.109	0.102	0.207	0.140	0.168	0.259	0.249
Gw2	0.270	0.199	0.242	0.144	0.142	0.218	0.152	0.245	0.358	0.185
Gw3	0.258	0.215	0.194	0.190	0.192	0.243	0.152	0.191	0.312	0.310
Gw4	0.333	0.296	0.296	0.307	0.308	0.348	0.268	0.331	0.396	0.307
Gw5	0.275	0.202	0.267	0.114	0.097	0.206	0.169	0.154	0.311	0.153
Gu1	0.189	0.193	0.159	0.109	0.160	0.129	0.140	0.153	0.174	0.162
Gu2	0.088	0.058	0.097	0.144	0.089	0.090	0.089	0.217	0.086	0.116
Gu3	0.181	0.163	0.134	0.190	0.095	0.108	0.107	0.261	0.228	0.236
Gu4	0.211	0.196	0.232	0.245	0.232	0.237	0.239	0.359	0.212	0.234

Table 6. Connection number evaluation results.

Connection Number	Results of Connection Number Evaluation in Different Years									
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
uw1	0.323	0.490	0.249	0.627	0.625	0.425	0.698	0.569	0.441	0.400
uw2	0.171	0.328	0.213	0.407	0.424	0.384	0.364	0.284	0.079	0.354
uw3	0.194	0.383	0.340	0.414	0.424	0.416	0.424	0.342	0.233	0.287
uw4	0.075	0.185	0.134	0.305	0.293	0.266	0.336	0.206	0.045	0.090
uw5	0.293	0.470	0.350	0.531	0.620	0.393	0.553	0.610	0.291	0.490
uu1	0.569	0.569	0.601	0.627	0.617	0.637	0.615	0.627	0.557	0.567
uu2	0.632	0.589	0.555	0.407	0.555	0.563	0.522	0.482	0.550	0.506
uu3	0.579	0.587	0.626	0.414	0.621	0.636	0.614	0.448	0.493	0.488
uu4	0.454	0.516	0.421	0.402	0.428	0.428	0.420	0.260	0.452	0.425

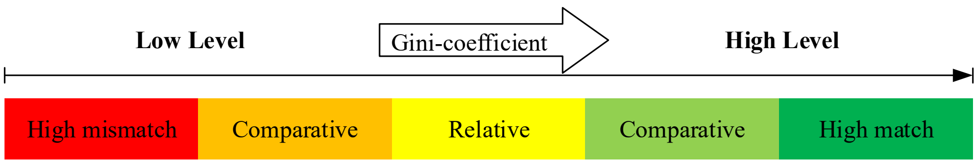

Figure 3. Gini coefficient evaluation criteria.

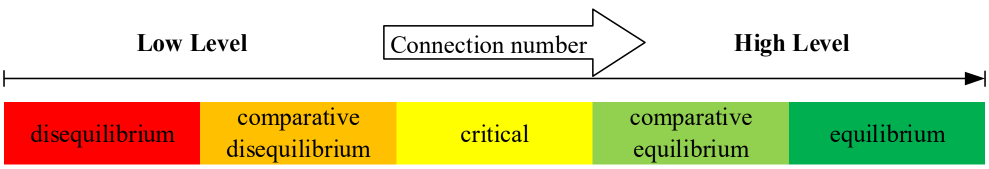

Figure 4. Connection number evaluation criteria.

3.1. Evaluation Results of the Spatial Equilibrium of the Total Water Resources in Tai'an City

According to the data analysis in Tables 5 and 6, the perennial average Gini coefficient of the total water resources and agricultural acreage in Tai'an city from 2011 to 2020 was 0.21, which is a relatively matched condition, and the perennial average correlation value was 0.47, which is a relatively balanced condition (level II). The annual average Gini coefficient of the total water resources and population was 0.22, which belongs to the comparison match, and the annual average correlation value was 0.30, which belongs to the critical (level III). The perennial average Gini coefficient of the total water resources–GDP of the secondary industry of Tai'an city from 2011 to 2020 was 0.23, which belongs to the comparative match class, and the perennial average correlation value was 0.35, which belongs to the critical (level III). The annual average Gini coefficient of the total water resources–GDP of the tertiary industry was 0.32, which is a relatively matched state, and the annual average correlation value was 0.18, which is a relatively unbalanced state (level IV). The perennial average Gini coefficient of the total water resources and agricultural irrigation water consumption in Tai'an city from 2011 to 2020 was 0.19, which is a highly matched state, and the perennial average correlation value was 0.46, which is a relatively balanced state (level III).

As shown in Figure 5, according to the trend whereby the lower the Gini coefficient is, the larger the connection number, the higher the connection value, and the more balanced the matching relationship of the different water resources, the trends of the two types of curves were the opposite, indicating that the evaluation results obtained by the above two methods were relatively consistent. Notably, in recent years, the spatial balance of the total water resources, agricultural acreage, population, GDP of the secondary industry, and agricultural irrigation water consumption in Tai'an city was satisfactory, and the distribution of water resources was relatively balanced, while the spatial balance of the GDP of the tertiary industry was general, and the distribution of water resources was relatively unbalanced.

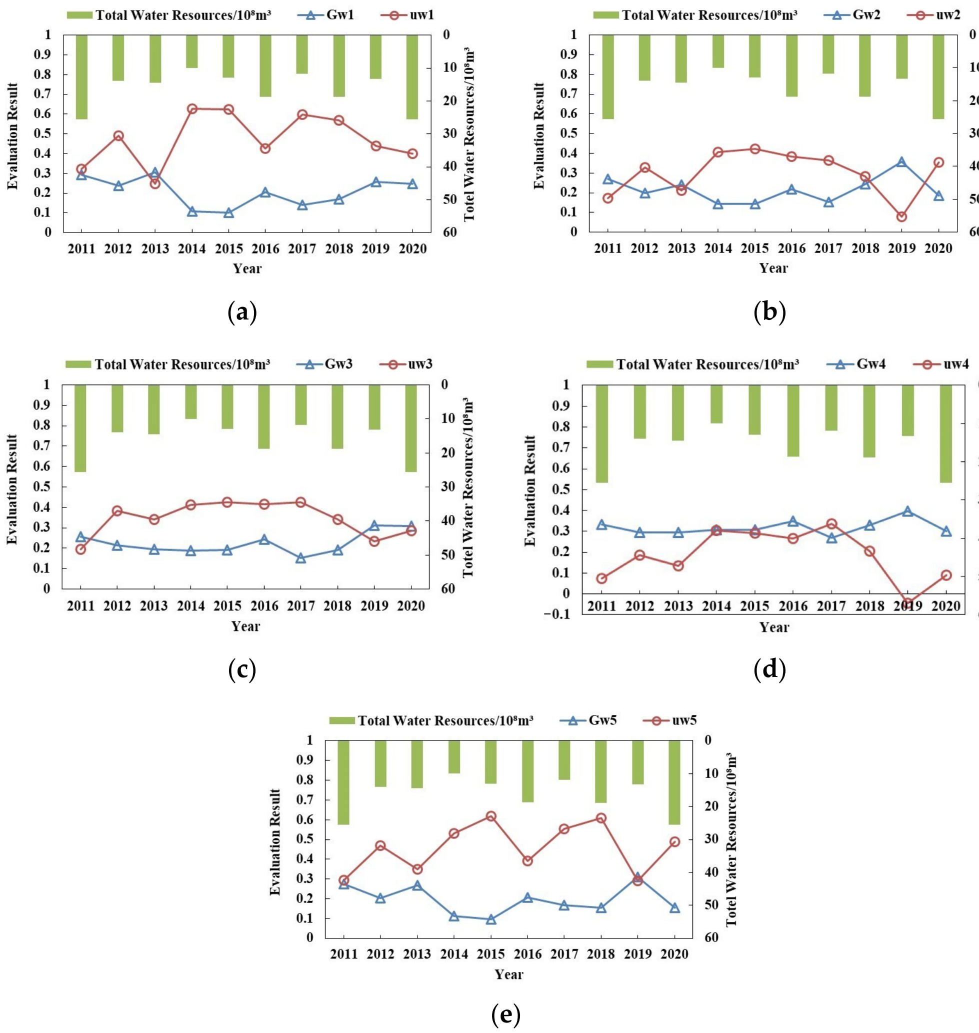

Figure 5. Evaluation results of the spatial equilibrium of the total water resources. ((**a**–**e**) represents the evaluation results of total water resources, cultivated land area, population, GDP of secondary industry, GDP of tertiary industry and water consumption of agricultural irrigation respectively.)

In the matching process of the total water resources and agricultural acreage, it was found that the equilibrium greatly changed in 2013 and 2016. In 2013, the water resources in Ningyang county and Dongping county continued to decrease by 36.49% and 10.61%, respectively, while the water resources in the other administrative regions increased. Moreover, the Gini coefficient increased, and the correlation value decreased, resulting in a poor distribution balance of the water resources in Tai'an city. In 2013, the water resources in Ningyang county and Dongping county continued to decrease by 36.49% and 10.61%, respectively, while the water resources in the other administrative regions increased. In 2016, the total water resources in Daiyue district increased by 106.69%, while the total water resources in Dongping county decreased by 11.47%. In Feicheng city and Ningyang county, the total water resources increased by 19.79% and 24.50%, respectively, while the corresponding agricultural acreage decreased by 7.79% and 19.04%, respectively, resulting in a poor balance of water resource allocation in Tai'an city. Moreover, the Gini coefficient increased and the correlation value decreased.

In the analysis of the matching process of the total water resources and population, although Daiyue district was established in 2019, the status and water resource quantity in Dongping county decreased, but the water resource quantity in Xintai city declined in two consecutive years, leading to the total water resource allocation balance in Tai'an city in 2019 reaching only the level of relative matching. In 2020, the water resources in Feicheng city decreased by 27.87%, further balancing the increase in water resources in 2018, while the population in Feicheng city decreased by 7.54% in 2020. The amount of water resources in Taishan district, Daiyue district, and Xintai city also increased with increasing population relative to that in 2019. In 2020, it increased by 403.76%, which also improved the equilibrium degree of the total water resources in the city.

The spatial equilibrium trend of the total water resources–GDP of the secondary industry in Tai'an city from 2011 to 2018 was slightly improved, and the equilibrium slightly declined in 2019 and 2020. In 2019, the water resources in Daiyue district, Feicheng city, and Dongping county decreased, but the extent was limited, and the water resources in Xintai city continued to decrease in two consecutive years. The GDP of the secondary industry in Xintai city, Ningyang county, and Dongping county decreased by 50.32%, 53.84%, and 62.33%, respectively, relative to 2018. This led to the total water resource allocation balance in Tai'an city in 2019 reaching only the level of relative matching. In 2020, the GDP of the secondary industry in each region increased in response to a lower equilibrium. Because the total water resources and the cultivated land area exhibited similar spatial equilibrium evaluation results, the balance of water resources in 2020 was lower.

The spatial balance of the total water resources–GDP of the tertiary industry in Tai'an city was general, and the distribution of water resources was unbalanced. In particular, in 2019, only the GDP of the tertiary industry of Daiyue district increased by 24.51%, while that in the other administrative regions decreased by varying degrees, especially in Ningyang county and Dongping county, where it decreased by 49.52% and 48.45%, respectively, relative to 2018. At the same time, compared to those in 2018, the water resources in Taishan district, Daiyue district, and Xintai city decreased by 41.17%, 54.68%, and 48.22%, respectively, which explains the poor balance of the total water resource allocation in 2019. Comparatively, the water resource matching equilibrium between the total water resources and GDP of the tertiary industry was highly inferior to that of the other matching objects and had not been effectively improved, which should be considered.

The spatial equilibrium trend of the total water resources and agricultural irrigation water consumption in Tai'an city from 2011 to 2020 slightly improved. The Gini coefficients in 2014, 2015, 2017, 2018, and 2020 were low, the correlation values were high, and the spatial equilibrium situations were favorable. The balance of the total water resources–agricultural irrigation water consumption roughly matched that of the total water resources–population. The balance of the total water resources in Tai'an city changed with the water resources in each administrative region, but the balance result was better.

3.2. Evaluation Results of the Spatial Equilibrium of the Total Water Use in Tai'an City

According to the data analysis in Tables 5 and 6, the perennial average Gini coefficient of the total water use and agricultural acreage in Tai'an city from 2011 to 2020 was 0.16, which is a highly matched state, and the perennial average correlation value was 0.60, which is the equilibrium state (level I). The annual average Gini coefficient of the total water use and population was 0.11, which is a highly matched condition, and the annual average correlation value was 0.54, which is a relatively balanced state (level II). The perennial average Gini coefficient of the total water use and GDP of the secondary industry was 0.17, which is a highly matched state, and the perennial average correlation value was 0.55, which is a relatively balanced condition (level II). The perennial average Gini coefficient of the total water use–GDP of the tertiary industry was 0.24, which is a relatively matched state, and the perennial average correlation value was 0.42, which is a relatively balanced state (level II).

As shown in Figure 6, the evaluation results obtained by the Gini coefficient method and correlation number method were relatively consistent with the spatial matching relationship of the total water resources, indicating that the spatial equilibrium situation of the total water use, agricultural acreage, population, GDP of the secondary industry, and GDP of the tertiary industry in Tai'an city has improved in recent years, and the distribution of water resources is relatively balanced.

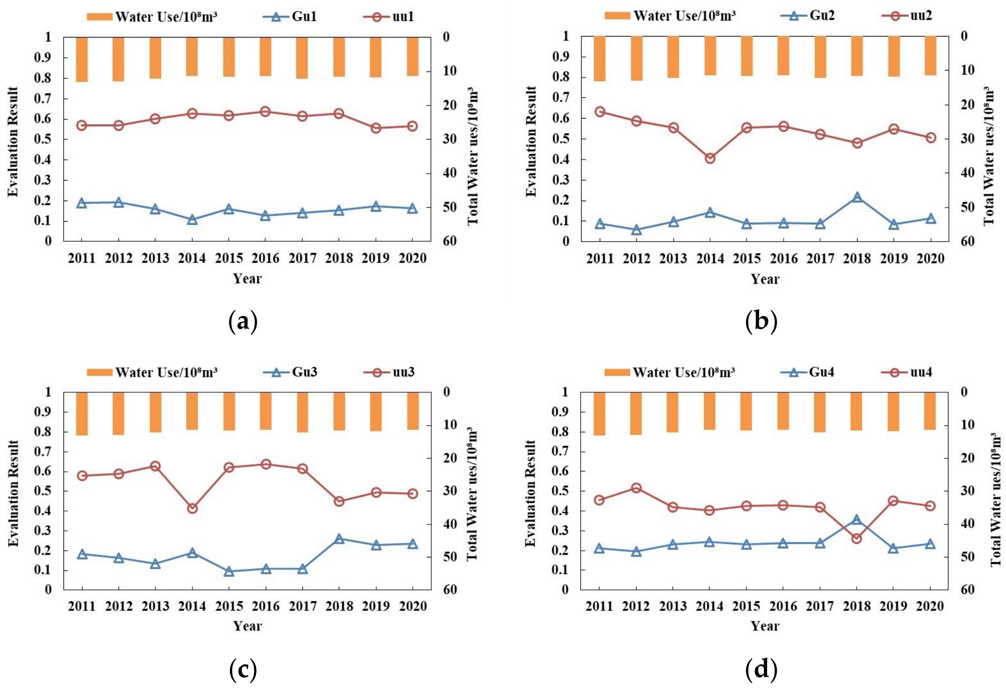

Figure 6. Evaluation results of the spatial balance of the total water use. ((**a**–**d**) represents the evaluation results of total water use, cultivated land area, population, GDP of secondary industry and GDP of tertiary industry respectively.)

The spatial equilibrium trend of the total water use and agricultural acreage in Tai'an city from 2011 to 2020 changed slightly overall. The Gini coefficient was low in all years, and the correlation value was high. In 2019, the total water use in Tai'an city increased by only 0.90%, but the water consumption in each administrative region greatly changed. Compared to that in 2018, the total water consumption in Taishan district, Daiyue district, Feicheng city, and Xintai city increased by 2.95%, 13.06%, 39.40%, and 65.98%, respectively. However, the water use in Ningyang county and Dongping county decreased by 39.12% and 37.01%, respectively, leading to a balanced distribution of the water resources in Tai'an city, reaching level II (relatively balanced). However, in 2020, the water use in Feicheng city and Xintai city decreased, but the amount of change was very small, and the water use in Taishan district decreased by 14.21%, so the balanced situation did not improve much. However, in general, the spatial balance improved.

The analysis of the spatial equilibrium trend between the total water use and population showed that there was a slight change overall. In 2014 and 2018, the Gini coefficient was high, the correlation value was low, and the spatial equilibrium situation was poor. In 2011 and 2012, the Gini coefficient was low, and the correlation value was high. However, in 2013 and 2014, the water use in Taishan district, Daiyue district, Feicheng city, and Xintai city continued to decrease by varying degrees, resulting in a poor distribution balance of the total water use in Tai'an city in 2014. In 2018, the water use in Daiyue district, Feicheng city, and Xintai city decreased by 16.29%, 30.48%, and 38.19%, respectively, while the water use in Ningyang county and Dongping county increased by 57.59% and 30.11%, respectively, resulting in a poor distribution balance of the total water resources in Tai'an city in 2018. When this situation was improved in 2019, the balance of the total water distribution in Tai'an city also improved.

In terms of the spatial equilibrium between the total water use and GDP of the secondary industry, the spatial equilibrium trend from 2011 to 2017 was slightly improved overall. In 2014, the Gini coefficient suddenly increased, and the correlation value decreased. In 2018, 2019, and 2020, the equilibrium situation was poor. In 2013 and 2014, the water use in Taishan district, Daiyue district, Feicheng city, and Xintai city continued to decrease by varying degrees, leading to deterioration in the distribution balance of the total water use in Tai'an city in 2014. Moreover, in addition to the decrease in the GDP of the secondary industry in Xintai city, the GDP of the secondary industry in the other administrative regions increased to varying degrees, which aggravated the imbalance of the total water distribution. Similarly, when the GDP of the secondary industry changed only slightly in 2018, the water use in Daiyue district, Feicheng city, and Xintai city decreased by 16.29%, 30.48%, and 38.19%, respectively, while that in Ningyang county and Dongping county increased by 57.59% and 30.11%, respectively, resulting in a poor balance of the total water resource allocation in Tai'an city in 2018. In 2019, although this situation was alleviated, the GDP of the secondary industry in each administrative region decreased to varying degrees. In particular, the values in Xintai city, Ningyang county, and Dongping county decreased by 50.32%, 53.84%, and 62.33%, respectively, relative to 2018. Therefore, the balance degree of the total water allocation in Tai'an city was not greatly improved in 2019. In 2020, the GDP and water consumption of the secondary industry in each administrative region slightly changed. Therefore, the balance degree of the total water use distribution in Tai'an city in 2020 did not change much.

The spatial equilibrium trend of the total water use–GDP of the tertiary industry from 2011 to 2020 varied slightly overall. The equilibrium situation was favorable in 2012 and the Gini coefficient was high in 2018, but the correlation value was low. Due to the distribution problem of the total water use in each administrative region in 2018, the GDP of the tertiary industry in each administrative region slightly increased to varying degrees, among which the GDP of the tertiary industry in Daiyue district increased by 8.28% relative to 2017, and the distribution balance of the total water use in Tai'an city in 2018 greatly changed, reaching only the critical state.

4. Discussion and Conclusions

In summary, the following discussion can be obtained:

The results showed that the total water resources and total water use distribution in each administrative region of Tai'an became more balanced, while the distribution of the secondary and tertiary industries became less balanced. However, since the other factors basically remained at the medium level, the water balance in Tai'an improved. This finding also verifies the reliability and applicability of research methods such as the Gini coefficient and variable fuzzy set when evaluating the spatial balance of water resources. Comparatively, the equilibrium degree between the water resources and GDP of the tertiary industry in Tai'an city was low, mainly due to either the uneven distribution of the water resource load in the various counties and urban areas or the different time scales. Yang et al. (2022) also analyzed various evaluation indexes for the Yangtze River Economic Belt by establishing a water resource spatial equilibrium evaluation model based on the Gini coefficient and variable fuzzy set. The results showed that during the entire study period, the spatial equilibrium state of the water resources in the Yangtze River Economic Belt remained stable (critical state), mainly because Shanghai and Jiangsu provinces in the Yangtze River Economic Belt contained fewer water resources. With a high population density and high GDP, the water resources in Zhejiang province are 2.57 times those in Jiangsu province. In contrast, the population and GDP in Zhejiang province are similar to those in Jiangsu province, but both the population and GDP in Sichuan province are higher than those in Shanghai. Some provinces exhibit great potential for agricultural water use, while other provinces attain medium levels of water resources and cultivated land, which is consistent with the conclusions of this study. The imbalance of the water resource load in the Yangtze River Economic Belt is the main factor interfering with the spatial distribution of water resources.

The calculation model and analysis method of the quantitative index of the equilibrium degree were studied, and then the Lorenz curve and correlation number methods were combined. Then, a quantitative evaluation method of the water resource spatial equilibrium was constructed based on the Lorenz curve and correlation number methods. Finally, the two methods were combined to quantitatively analyze the equilibrium degree of water resources and economic and social development. The quantitative results can comprehensively reflect the equilibrium of regional water resource factors and economic and social development factors. Furthermore, to address the total water resources matching relationships, this study included research on the balance between the total water resources and cultivated land area, population, and GDPs of the secondary industries, thus increasing the research scope. This comparison better reflects the spatial balance of the water resources in Tai'an city. The water resources in river basins are key determinants of regional development [27,46]. An in-depth analysis of the degree and state of the water resource balance based on the literature can support the efficient utilization of water resources and promote coordinated development of water resources and economic, social, and environmental factors [47–49]. Based on the satisfaction function and Gini coefficient, Chen et al. built an equilibrium function as a guide and introduced Maslow's hierarchy of needs theory to improve the water resources regulation model. The water resources in the Yellow River basin are controlled in a spatiotemporal equilibrium, which greatly ensures the water security rate [29]. According to the requirements put forward in the 14th Five-Year Plan for national economic and social development of Tai'an city and the outline of the 2035 vision goal, combined with the results of the research and analysis on the spatial equilibrium of water resources in Tai'an city in the past ten years, the law that the smaller the Gini coefficient is, the more balanced the spatial distribution of water resources can be combined with other theoretical support in the future. It can adjust the industry and water replenishment and water transfer, optimize the rational allocation of water resources, ensure that the Gini coefficient is reduced and kept stable, especially the matching relationship between the total water resources and the GDP of the secondary industry, and improve the utilization of industrial water resources, which is urgent.

By combining the Lorenz curve, Gini coefficient and correlation number methods, this study draws the following conclusions:

(1) The average Gini coefficients of the total water resources in Tai'an city from 2011 to 2020 were 0.21, 0.22, 0.23, 0.32, and 0.19 for the arable land area, population number, GDP of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water consumption, respectively. The correlation values were 0.47, 0.30, 0.35, 0.18, and 0.46, respectively. The average Gini coefficient values of the total water use, cultivated land area, population, GDP of the secondary industry, and GDP of the tertiary industry in Tai'an from 2011 to 2020 were 0.16, 0.11, 0.17, and 0.24, and the correlation values were 0.60, 0.54, 0.55, and 0.42, respectively. In Tai'an city, the proportion of dry

years from 2011 to 2020 reached 60%. Continuous drought resulted in an unbalanced spatial distribution and regional distribution of water resources and is an important reason for the difference in the equilibrium degree according to the different matching relationships [50].

(2) An empirical study of the spatial equilibrium matching relationship between the total water resources and total water use in Tai'an city, cultivated land area, population number, GDP of the secondary industry, GDP of the tertiary industry, and agricultural irrigation water consumption was conducted. The results showed that the total water use–cultivated land area and total water use–population in Tai'an city from 2011 to 2020 exhibited a spatial equilibrium state. The total water resources–arable land area, total water resources–agricultural irrigation water consumption, total water use–GDP of the secondary industry, and total water use–GDP of the tertiary industry occurred in a relatively balanced state. The total water resources–population and total water resources–GDP of the secondary industry indicated a critical state. The total amount of water resources–GDP of the tertiary industry exhibited a relatively unbalanced state in space. In particular, the balance between the total water resources and the GDP of the secondary industry was poor and must be improved.

(3) An uneven distribution of the total water resources in Tai'an city was obtained. River runoff in Tai'an city is mainly fed by precipitation, and the regional distribution trend of the annual runoff depth is basically consistent with that of precipitation. However, because runoff is affected by the underlying surface, the distribution of the annual runoff depth is more uneven than that of the annual precipitation. The distribution trend decreased from the eastern hilly area to the western plain area and in-creased from the eastern hilly area to the western plain area. The water resources in Tai'an city mainly stem from atmospheric precipitation. Due to the high interannual and annual variations in atmospheric precipitation, the amount of water resources also exhibits similar characteristics, resulting in large interannual fluctuations in the total amount of water resources. However, except for a small increase in 2017, the total water consumption decreased year by year and basically remained stable.

It is suggested that under the premise of comprehensively strengthening water conservation and strengthening the rigid constraint of water resources, moderate water replenishment and transfer should be carried out, scientific and reasonable allocation of water resources should be carried out, and the secondary industry should be upgraded or industrial parks should be built in appropriate areas, so as to avoid the deeper impact on areas with severe water shortage as far as possible. It is also necessary to judge the utilization situation and carrying capacity of water resources in Tai'an city, put forward the development ideas in line with the 14th Five-Year Plan and high-quality development, and put forward the overall plan of water supply and demand balance, which is of great significance for making full use of water resources, realizing the balanced and optimal allocation of water resources, and ensuring water security in Tai'an city.

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