Analysis of regional water resources spatial pattern and allocation equity

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Abstract. Water scarcity is a worldwide concern, and with the impact of climate change and human activities, the imbalance in the distribution of water resources has further intensified. The equitable allocation of water resources has become a thorny issue for water resources management authorities. It is challenging to find a relatively equitable method of water resources allocation. This study aims to propose a method for evaluating the fairness of water resources allocation, which can be used both to evaluate the fairness of water resources allocation and as a basis for water resources allocation decisions. The specific approach is to first analyze the spatial pattern of regional water resources by using water resources abundance and water resources intensity, and then to conduct a comprehensive analysis of regional water resources allocation fairness by combining Lorenz curve, Gini coefficient and Theil index to form an index system that can systematically analyze the spatial pattern of water resources, allocation fairness and its changes. A real-world example study was conducted in the Yangtze River Delta region of China, and the results showed that the index system can well reflect the allocation of water resources among regions and cities within the region. The results obtained using this method can provide some reference for promoting coordinated regional development.

Keywords: spatial pattern; allocation equity; Lorenz curve; Gini coefficient; Theil index.

1. Introduction

Water resources are the basic resources on which human beings depend, and the study of water resources allocation has received more and more attention [1]. The artificial division of administrative regions makes the same river flow through different administrative regions, and the process of water resources allocation usually involves different interest subjects. When the allocatable water resources are not enough to meet the water demand of the whole region, conflicts may arise between regions due to the competition for scarce water resources. In the case of water shortage, water allocation has become an important means to solve regional water-related conflicts. In addition, water resources allocation, as an important part of water resources sustainable development and management research, is of great significance to ensure the basic water needs of ecological environment, improve the comprehensive utilization efficiency of water resources, and realize the efficient and equitable use of water resources.

Since the 1950s, scholars have begun to explore the problem of rational water resources allocation, from system engineering analysis and simulation to water resources allocation focusing on ecological and social equity, and have conducted a lot of research on theoretical methods, mechanisms and allocation results of water resources allocation [2], thus laying a theoretical foundation for the fair allocation of water resources. The studies on water resources allocation can be divided into two categories: (1) descriptive studies on water resources allocation covering political aspects; and (2) quantitative studies on water resources allocation covering technical aspects.

Descriptive water allocation studies covering political aspects are concerned with the rules of the water allocation process and the political negotiations between regions. The Political Accounting System (PAS) was the first mathematical model to measure political negotiation [3] and was applied to water allocation problems [4-5] proposed a model similar to PAS in 1994 to determine the relative rights between regions and applied the model to Middle Eastern rivers.

Kucukmehmetoglu and Gludmann [6] considered the influence of political factors in applying the water allocation model to the Euphrates and Tigris rivers.

Quantitative studies of water resources allocation based on simulation optimization, water rights, and complex adaptive systems has also been widely carried out. For example, Van et al. proposed six quantitative criteria that can achieve equitable water allocation in international rivers, and applied the proposed quantitative criteria for equitable water allocation to the Orange, Nile, and Intramati rivers, respectively, to allocate water according to the basin area, the proportion of population in the basin, etc. can achieve reasonable water resources allocation area, the proportion of population in the basin, etc. can achieve reasonable water resources allocation [7].Kampragou et al. [8] developed an indicator system for transboundary water resources allocation based on the natural conditions, socio-economic and sustainable development of each region of transboundary water resources and applied it to the transboundary river Nystos. Ansink and Weikard [9] extended the sequential sharing rules (SSRs) and applied them to transboundary water resources management. Zarezadeh et al. [10] applied four water allocation rules, namely PRO, APRO, CEA and CEL, to Iran under different climatic scenarios, respectively, under the same climatic scenario. Abolpour et al. applied the Adaptive Neural Fuzzy Inference System (ANFIS) method to water resources allocation in Iran under different climatic conditions. Abolpour et al. [11] applied the Adaptive Neural Fuzzy Inference System (ANFIS) method to water allocation in Iran. Ding et al. [12] proposed a trans-regional water resource allocation model based on parallel evolutionary search algorithm, i.e., by reallocating water resources among competing agents based on their contributions to the central solution. Arjoon et al.

Under the increasingly severe situation of worldwide water scarcity and trans-regional water resources conflicts, higher requirements are put forward for the fair and reasonable distribution of water resources [13]. Countries are also facing complex and volatile cross-regional water resources conflicts [14]. However, there is no internationally accepted standard for water resources allocation, mainly because of the differences in geopolitical, socioeconomic and environmental factors between regions [15]. It is challenging to find a water allocation approach that is acceptable to all regions. Moreover, the existing studies mentioned above also focus on the method of allocation, often neglecting the evaluation of the equity of the current resources water allocation or the equity after allocation.

This paper is a precursor study to our project for optimized allocation of water resources in a changing environment. The purpose of this paper is to propose a method for evaluating the equity of water resources allocation, which can be used both for the evaluation of equity of water resources allocation and as a basis for decision making on water resources allocation. This study introduces water resources abundance and water resources intensity to investigate the spatial pattern of regional water resources, and combines the Lorenz curve, Gini coefficient and Theil index to conduct a comprehensive analysis of regional water resources allocation equity, forming an index system that can systematically analyze the spatial pattern of water resources, allocation equity and its changes.

2. Methods

2.1 Spatial pattern of water resources

The spatial pattern of water resources is mainly characterized by the abundance and intensity of water resources. Water abundance is calculated by dividing a region's total water resources by the region's land area. The water resource intensity is the water resource consumption intensity, which is obtained by dividing the water resource consumption of a region by the GDP of the region, and reflects the water resource utilization efficiency in the production process of the region.

2.2 Allocation equity of water resources

In order to quantitatively analyze the allocation equity of water resources, this paper introduces the Lorenz curve and the Gini coefficient. The Lorentz curve is a commonly used indicator in economics and statistics. It is mainly used to describe the inequality of income distribution. It is also widely used to describe and measure the unevenness and concentration of distribution. Its mathematical expression is

$$L(y) = \frac{\int_0^y x dF(x)}{\mu} \tag{1}$$

where F(x) is the cumulative distribution function of each region; μ is the mean.

Generally, the greater the curvature of the Lorentz curve, the more uneven the distribution of the two variables, and the closer to the diagonal (absolute mean line), the more equitable the distribution of the two variables.

In order to further describe the Lorentz curve quantitatively, Gini defines the ratio of the area enclosed by the actual Lorentz curve and the absolute mean line to the area between the absolute mean line and the absolute uneven line as the Gini coefficient, which is evaluated according to internationally recognized standards, as shown in Table 1.

In this study, based on the water consumption and social-economic indicators of the urban agglomeration, the cumulative percentage of water resources is taken as the horizontal axis, and the cumulative percentage of social-economic indicators is taken as the vertical axis, and the corresponding relationship curve is drawn, which is Lorentz curve, on the basis of which the corresponding Gini coefficient is calculated. This method takes the following assumptions as the premise: in the process of human social development, the matching relationship between the total output value (population, GDP, cultivated land, etc.) and the consumption of water resources is relatively balanced in space.

Table 1 Gini coefficient division standard.

Gini coefficient	Evaluation standard
0~0.2	Best equity
0.2~0.3	Comparative equity
0.3~0.4	Reasonable
0.4~0.5	Relative inequality
Above 0.5	Extreme inequality

2.3 Theil index

The Theil index was proposed by Dutch economist Theil based on information theory and was initially used to study the income gap between countries. The larger the Theil index, the greater the gap between the index values between the samples, and the more unfair it is. On the contrary, the fairer it is. The Theil index equal to 0 means absolute fairness. Because the Theil index can decompose the overall difference into inter-regional differences and intra-regional differences, scholars have gradually used it widely in the evaluation of regional economic differences. Based on the above analysis results of the allocation equity of water resources, this study further uses Theil index to analyze the causes of the inequity. As for the Yangtze River Delta region, since Shanghai is a municipality directly under the Central Government, this study mainly considers decomposing the corresponding overall differences in the Yangtze River Delta region into differences between cities within Jiangsu, Zhejiang, and Anhui, as well as differences between the three provinces. Analyze the contribution of various types of differences to the overall difference, so as to find out the main reasons for the unfair allocation of water resources. The formula for calculating the Theil index decomposition is:

$$T_{ID} = \sum_{j=1}^{3} \frac{E_j}{E} \sum_{i=1}^{m} \left[\frac{E_{ji}}{E_j} \ln \left(\frac{E_{ji}/E_j}{W_{ji}/W_j} \right) \right] \tag{2}$$

$$T_{RD} = \sum_{j=1}^{3}\left[\frac{E_j}{E}\ln\left(\frac{E_j/E}{W_j/W}\right)\right] \quad (3)$$

$$T_D = T_{ID} + T_{RD} \quad (4)$$

where T_D is the total Theil index value, T_{ID} is the difference between cities, T_{RD} is the difference between the three provinces. m is the number of cities. E_{ji} is the social-economic indicator of city i in province j. E_j is social-economic indicator of province j. W_{ji} is the water consumption of city i in province j, W_j is the water consumption of province j.

3. Study Area and Basic Data

3.1 Study Area

China is a country with relatively scarce water resources, with the per capita water resources only accounting for a quarter of the world average. A series of factors such as climate change, population growth, environmental degradation and socio-economic development have led to the intensification of the conflict between supply and demand of water resources. Water shortage has become an important factor limiting sustainable socio-economic development [16]. The Yangtze River Delta region is one of the most active regions in China's economic development, and its total economic volume accounts for about a quarter of the country's total GDP of about $3,514.7 billion in 2019 and is the wind vane of China's economy. In 2019, the Yangtze River Delta region has an urbanization rate of nearly 70% and accounts for about 16.8% of the country's total water consumption and only 7.4% of water resources. In addition, the development of the provinces and cities in the Yangtze River Delta is particularly uneven. In terms of GDP per capita, the largest city, Wuxi, is 5.5 times larger than the smallest city, Fuyang. Therefore, this study selects the Yangtze River Delta region of China as a case to conduct an analysis regional water resources spatial pattern and allocation equity. The results can provide a reference for water resources allocation studies in other regions.

The Yangtze River Delta region involves Jiangsu province, Zhejiang province Anhui province and Shanghai city, with an area of 358,000 km^2. And it involves three water resource zones: the Yangtze River basin, the Huaihe River basin and the southeastern rivers basin, which account for 35%, 37% and 28% of the total area, respectively. In this study, 41 cities in the Yangtze River Delta region were selected, and the spatial pattern of water resources and the equity of water resources allocation are studied using the analysis method proposed. The schematic diagram of the study area is shown in Figure 1.

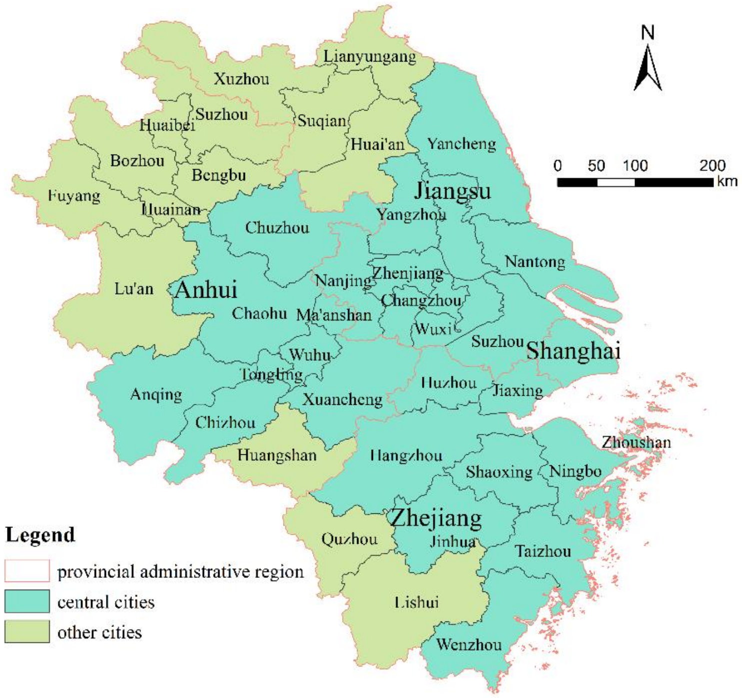

Fig. 1 Map of the Yangtze River Delta region

3.2 Data Source

Water resources and water consumption data in this study were obtained from the water resources bulletins of Jiangsu, Zhejiang, Shanghai, and Anhui provinces from 2015-2019. Socio-economic development indicators were obtained from the statistical yearbooks of each province. Socio-economic indicators include population, GDP, industrial value added, and actual irrigated area of farmland.

4. Results

4.1 Spatial pattern of water resources

4.1.1 Abundance of water resources

A Figure 2 shows the spatial distribution of water resource abundance in the Yangtze River Delta urban agglomeration in 2019. Among them, Taizhou, Quzhou, etc. in Zhejiang Province have the highest water resource abundance, all reaching more than 1.2 million m^3/km^2; Secondly, Hangzhou, Shaoxing in Zhejiang Province, Huangshan in Anhui Province, etc. are relatively rich in water resources, ranging from 800,000 to 1.2 million m^3/km^2; The abundance of water resources in 14 cities including Yangzhou, Taizhou, etc. is relatively low, all below 200,000 m^3/km^2. It can be seen that cities with high water resources abundance are mainly distributed in Zhejiang Province, and cities with low water resources abundance are mainly distributed in Jiangsu Province and most parts of Anhui Province. There are great differences in the abundance of water resources in different cities. Since Shanghai, Jiangsu, and Anhui are located in the lower reaches of the Yangtze River, there are abundant water resources in transit available for use, so the local water production in each city cannot fully reflect the allocation of water resources. Therefore, this paper mainly studies the allocation equity of water resources by using water consumption in each city and the corresponding social and economic development indicators.

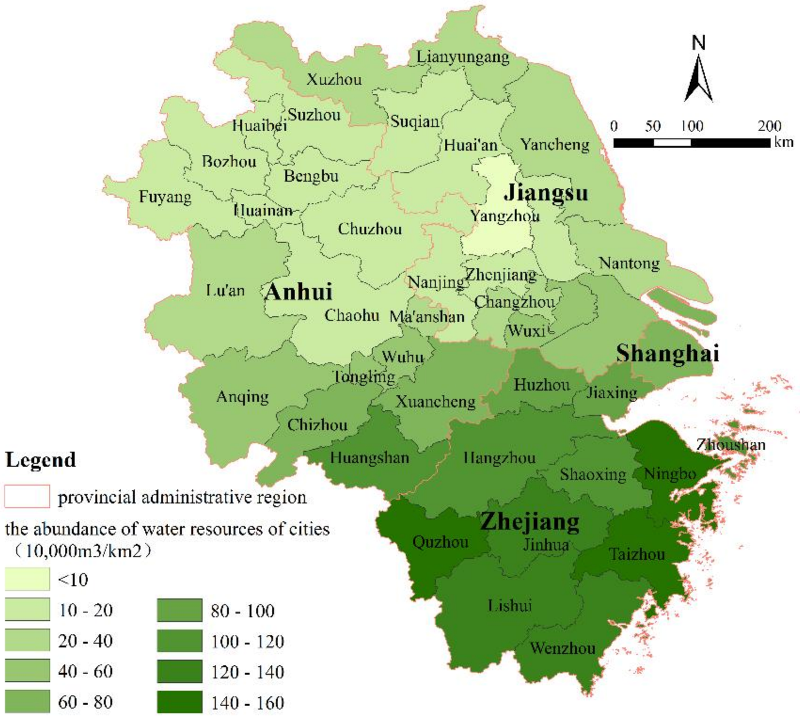

Fig. 2 Abundance of water resources of the Yangtze River Delta region

4.1.2 Intensity of water resources

The spatial distribution of water resources intensity in the Yangtze River Delta urban agglomeration in 2019 is shown in Figure 3. Among them, Huainan, Lu'an, Ma'anshan and Tongling have the highest water resource intensity, all exceeding 130 m^3/10,000 yuan, indicating that their water resource utilization efficiency is low; Secondly, the water resource intensity of Chizhou, Lianyungang, Anqing and Suqian is also relatively high, ranging from 100 to 130 m^3/10,000 yuan; The water resource intensity of 22 cities including Zhoushan, Ningbo, etc. is lower than the national average (60.8 m^3/10,000 yuan), and the water resources intensity of Zhoushan, Ningbo, and Shanghai is even lower than 20 m^3/10,000 yuan, It shows that their water resource utilization efficiency is high. It can be seen that the cities with high water resource intensity are mainly distributed in the western and southern regions of Anhui Province and the northern region of Jiangsu Province, and the cities with low water resources intensity are mainly distributed in Shanghai and Zhejiang Province. The water resources intensity of Shanghai and cities in Zhejiang Province is lower than the national average level. There are also certain differences in water resources intensity among cities.

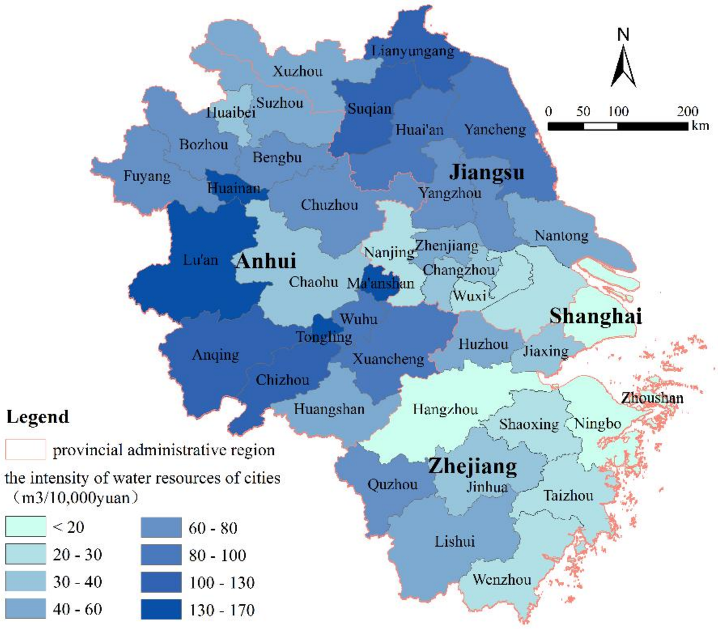

Fig.3 Abundance of water resources of the Yangtze River Delta region

4.2 Allocation equity of water resources

Build an analytical model for a series of indicators of water consumption and social-economic development of the Yangtze River Delta urban agglomeration, and draw the Lorenz curve in 2019 (as shown in Figure 4), and calculate the Gini coefficient (as shown in Table 2) and Theil index (as shown in Table 3) from 2015 to 2019 in order to quantitative analyze the allocation equity of water resources in the Yangtze River Delta region.

4.2.1 Lorenz curve and Gini coefficient analysis

From the perspective of society and agriculture, the Lorentz curve bending phenomenon of water consumption and population, farmland irrigation water consumption and farmland actual irrigation area in 2019 is more obvious. The Gini coefficients from 2015 to 2019 were 0.23 to 0.25 and 0.16 to 0.20, which were at comparatively equity level. It shows that the population and water consumption, the actual irrigated area of farmland and farmland irrigation water consumption in the Yangtze River Delta are basically coordinated in space, and the allocation is relatively fair.

From an economic and industrial point of view, the Lorentz curve bending phenomenon of water consumption and GDP, industrial water consumption and the added value of industry in 2019 is more obvious. From 2015 to 2019, the Gini coefficients were 0.33-0.34 and 0.32-0.35, respectively, which were in a relatively reasonable state, and the fairness of the allocation of water resources was not as good as that of society and agriculture, and there was room for further improvement.

In terms of time, the Gini coefficients of water consumption and population, water consumption and GDP, industrial water consumption and the added value of industry did not change much. The Gini coefficient of farmland irrigation water consumption and farmland irrigated area has a fluctuating upward trend, changing from the best equity state to a comparatively equity state, indicating that the allocation equity of water resources from the perspective of agriculture has a downward trend.

Judging from the water consumption indicators in 2019 (as shown in Table 3), the per capita comprehensive water consumption in the Yangtze River Delta is 446 m^3, slightly higher than the national average of 431 m^3, and the per capita comprehensive water consumption of 22 cities is greater than the national average. The water consumption per 10,000 yuan of GDP (that is, the water resource intensity) is 42.6 m^3, which is lower than the national average of 60.8 m^3, and the water resource intensity of 19 cities is higher than the national average. The water consumption per 10,000 yuan of added value of industry is 34.4 m^3, which is lower than the national average of 38.4

m^3, and the water consumption per 10000 yuan of added value of industry in 13 cities is higher than the national average. The average water consumption per acre of farmland irrigation is 361 m^3, which is equivalent to the national average level of 368 m^3, and the average water consumption per acre of farmland irrigation in 19 cities is higher than the national average. It can be seen that there are also certain differences in the water consumption indicators among cities in the Yangtze River Delta, and the water resource utilization efficiency needs to be further improved.

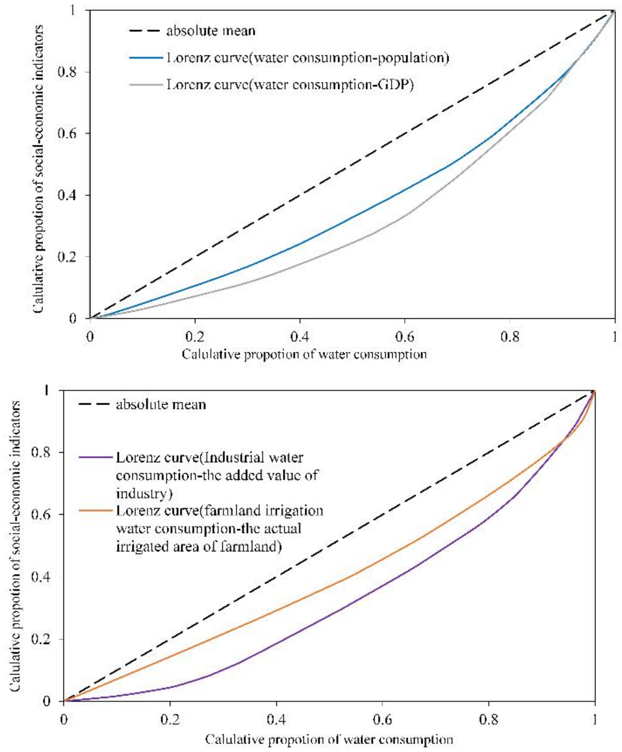

Fig. 4. The Lorenz Curve of water consumption and social-economic development indicators

Table 2 Gini coefficient of water consumption and social-economic development indicators

Year	Water consumption - population	Water consumption - GDP	Water consumption of industry - Added value of industry	Water consumption of farmland irrigation - Actual irrigated area of farmland
2015	0.23	0.34	0.32	0.16
2016	0.23	0.34	0.33	0.16
2017	0.24	0.34	0.33	0.15
2018	0.24	0.33	0.35	0.17
2019	0.25	0.34	0.34	0.20

Table 3 Water consumption indicators (unit: m^3)

Area	Comprehensive water consumption per capita	Water consumption per 10,000 yuan of GDP	Water consumption per 10,000 yuan of added value of industry	Average water consumption per acre for farmland irrigation
Yangtze River Delta region	446	42.6	34.4	361
National average	431	60.8	38.4	368

4.2.2 Theil index analysis

From the results of the Gini coefficient, the allocation of water resources from an economic and industrial perspective is at a relatively appropriate level, but there is still room for further improvement. The distribution map of water resources intensity also reflects that there are certain spatial differences in water consumption in Jiangsu Province from economic perspective. Based on the Theil index, the overall spatial differences in water consumption from economic and industrial perspective are decomposed into the differences between cities within Jiangsu, Zhejiang, and Anhui, as well as the differences between the three provincial-level administrative regions. The differences for each type and their contribution to the overall difference are shown in Table 4.

The results show that the total Theil index values from 2015 to 2019 are all greater than 0, indicating that there is a certain unfair phenomenon in the allocation of water resources in the Yangtze River Delta region from the perspective of economy and industry. The contribution rates of differences between cities within the region are 81.4%-82.3% and 77.2%-86.3%, respectively, indicating that the unfairness of water resources allocation based on economic and industrial perspectives is mainly caused by the differences between cities within the region. Economically, the differences between cities within Jiangsu and Anhui provinces are larger than that within Zhejiang. From an industrial point of view, the differences between cities within Jiangsu Province are relatively large, and that within Anhui Province are gradually decreasing.

Table 4 Decomposition of overall spatial differences in water consumption from economic and industrial perspectives

Perspectives	Year	Differences between cities within the region					Regional differences		Overall Spatial Difference
		Jiangsu	Zhejiang	Anhui	Total contribution value	Contribution rate	Contribution	Contribution rate	
Economy	2015	0.12	0.08	0.14	0.33	82.6%	0.07	17.4%	0.40
	2016	0.11	0.07	0.13	0.32	81.4%	0.07	18.6%	0.39
	2017	0.11	0.07	0.14	0.31	81.6%	0.07	18.4%	0.39
	2018	0.12	0.06	0.14	0.32	83.4%	0.06	16.6%	0.38
	2019	0.12	0.06	0.13	0.31	82.3%	0.07	17.7%	0.38
Industry	2015	0.14	0.07	0.14	0.35	86.3%	0.06	13.7%	0.41
	2016	0.13	0.07	0.13	0.34	83.9%	0.06	16.1%	0.40
	2017	0.12	0.08	0.14	0.33	84.7%	0.06	15.3%	0.39
	2018	0.14	0.11	0.12	0.37	85.3%	0.06	14.7%	0.43
	2019	0.15	0.07	0.07	0.28	77.2%	0.08	22.8%	0.37

5. Discussion and Conclusion

5.1 Disscussion

5.1.1 Spatial pattern and allocation equity

In this study, the spatial pattern of regional water resources was analyzed according to the abundance and intensity of water resources. The cities with high water resource abundance in the Yangtze River Delta are mainly located in Zhejiang Province, while the cities with low water resource abundance are mainly located in Jiangsu Province and most of Anhui Province. Cities with high water resource intensity are mainly located in the western and southern areas of Anhui Province and northern Jiangsu Province, while cities with low water resource intensity are mainly located in Shanghai and Zhejiang Province. There are some differences in the abundance and intensity of water resources in different cities. The Lorenz curve, Gini coefficient and Theil index were introduced to analyze the allocation equity of water resources. From the economic and industrial perspectives of the Yangtze River Delta region, the bending phenomenon of the Lorenz curve is more obvious, and its Gini coefficients from 2015 to 2019 are above 0.3, and the total Theil index is greater than 0. This indicates that there is a certain inequity in the allocation of water resources from the economic and industrial perspectives, and there is room for further improvement.

The differences in the degree of development of the Yangtze River Delta urban agglomerations were further analyzed based on the socio-economic indicators and water consumption data in 2019. From the perspective of urbanization development, there are also some differences in urbanization rates in the Yangtze River Delta region. Shanghai and Nanjing are at the forefront of the urbanization process in the country. Shanghai's urbanization rate is over 90% and Nanjing's is over 80%, but the urbanization rates of Bozhou, Suzhou, Fuyang, Luan and Anqing in Anhui Province are less than 50%. From the perspective of water resources development and utilization, the Yangtze River Delta region has a high utilization rate of water resources development. The overall water resources development and utilization rate in the central cities exceeds 50%, and the water consumption in cities such as Shanghai and Jiangsu exceed the local water production, mainly because Shanghai, Jiangsu and Anhui provinces are located in the lower reaches of the Yangtze River and have more transit water resources available. In some cities, such as Lishui and Quzhou in Zhejiang Province and Huangshan in Anhui Province, the utilization rate of water resources development is less than 10%, yet the abundance of water resources exceeds 1 million m^3/km^2. The social and economic development of these areas is relatively lagging behind. Rational allocation of water resources, optimal scheduling and improvement of corresponding regulatory mechanisms are of great significance to improve the equity of water resources allocation and promote the coordinated development of the Yangtze River Delta region.

5.1.2 limitations of the proposed mode

Water ecology and water environment are concomitant processes of the watershed water cycle that are currently receiving increasing attention. The scope of water allocation has also been expanded from a single socio-economic water allocation to develop in the basin socio-economic system and the basin ecosystem. However, this study only considered water resources allocation based on quantity rather than quality. Therefore, appropriate models that include water ecology and water quality related parameters, such as ecological flows and pollutants entering the river, could be considered in future studies. A more comprehensive quantitative and qualitative integrated evaluation model can be developed to facilitate water resources allocation studies that combine water ecology and water environment.

5.2 Conclusion

This study proposes a method for evaluating the fairness of water resources allocation, which can be used both to evaluate the fairness of water resources allocation and as a basis for water resources allocation decisions. The spatial pattern of regional water resources was firstly analyzed by using water resources abundance and water resources intensity, and then the equity of regional water resources allocation was comprehensively analyzed by combining Lorenz curve, Gini coefficient and Theil index, forming an index system that can systematically analyze the spatial pattern of water resources, the equity of allocation and its changes. A case study of the Yangtze River Delta region in China was conducted. From the agricultural perspective, water resources allocation in the Yangtze River Delta region is spatially coordinated, but there is a decreasing trend of equity. However, from an economic and industrial perspective, there is a certain inequity in water resources allocation, with relatively large differences between cities in the interior of the region. The case study showed that the index system can well reflect the allocation of water resources among regions and cities. The results obtained using this method can provide some reference for promoting coordinated regional development.

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