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Analysis of the rational allocation of regional reclaimed water based on the system coupling coordination criterion

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ABSTRACT

Chinese cities have developed rapidly in the past several decades, and the urban water shortages have become increasingly severe. The use of recycled water can effectively alleviate the imbalance between urban water supply and demand. We selected five areas in Suzhou as the study area, and a coupling coordination degree model of the water resources–economy–environment–reclaimed water system in each district and county-level city of Suzhou was constructed and analyzed. The characteristics of the regeneration water configuration scheme that corresponded to the optimal coupling coordination degree were derived. Downtown Suzhou had the best integrated development and system coupling coordination, while the other areas performed better when they were geographically closer to downtown Suzhou. In addition, different reclaimed water allocation schemes could be used to regulate the system coupling coordination of the region. For the Suzhou downtown area, increasing the amount of supplemental reclaimed water from the river landscape was an effective solution for promoting this coordination, and an increase in the total amount of reclaimed water utilized in other county-level cities also improved the coordination degree. This study provides lessons and references on how reclaimed water utilization can improve integrated and coordinated urban development.

Keywords: Water resources–economy–environment–reclaimed water system; Coupling coordination; Criteria; Reclaimed water allocation

1. Introduction

Water is an essential element for human survival, and it is an important strategic resource for social and economic development. The current regional imbalance between water supply and demand in China has become increasingly serious. By 2030, China's per capita water supply is estimated to be reduced to 1,800 m^3, with a water deficit of 201 billion·m^3 [1]. On the economic front, China's Gross Domestic Product (GDP) has steadily ranked second in the world, but the inter-provincial development gap is widening, and development in eastern and western China is uneven [2]. Although the quality of the water environment has greatly improved, economic development and ecological protection of the environment have not yet reached a balance, and local environmental pollution problems still exist to varying degrees. The problem of water scarcity and the large amount of wastewater discharged has stimulated research into the potential of recycled water treatment and reuse. Fig. 1 shows that water resources, the economy, the environment, and recycled water are all connected in China's socioeconomic development. Rapid economic development will increase the demand for water resources and may also cause pollution to the water ecosystem. The utilization of reclaimed water can alleviate the pressure on water resources by reusing polluted water while promoting a healthier ecological environment. To promote the comprehensive green transformation of economic

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and social development, it is necessary to study and analyze the coupling coordination degree of the water resources–economic–environment–reclaimed water (WEER) system under different levels of socio-economic development.

The present study is based on the coupled coordination degree model, and it has the aim of adjusting the reclaimed water allocation scheme. The coupled coordination degree model was first derived from the concept of the degree of coordinated development of the environment and economy in the Pearl River Delta city cluster [3]. The initial coupling coordination model was incomplete. Modifications to conventional models based on existing binary and ternary coupled coordination models could broaden the model's applicability [4]. Furthermore, the coefficient determination method of the coupled coordination model could be improved according to the development level [5]. One of the most multidimensional coupling studies currently available is a six-dimensional coupled coordination model [6]. The theory of coupled coordination is now well established, but there remains wide variation in the choice of systems for coupling. Current research often applies binary coupling to socio-economic and ecological environments [7–9], and ternary coupling analysis mainly focuses on resources (energy), the environment, and the economy [10–13]. Overall, although research on domestic four-system coupling is not uncommon, fewer studies have included reclaimed water in their coupling analysis. This study incorporates the reclaimed water system into the coupled coordination model, and thus can provide a theoretical perspective for the study of the multidimensional coupling of reclaimed water.

Initial research on the allocation of renewable water resources began in the United States. Generally, the cost of treatment and transportation should be considered in the configuration of recycled water [14]. The minimum water supply cost from multiple water sources is often employed as the objective function, and factors such as the water quality and treatment process have been considered to develop a more flexible nonlinear programming model [15]. For agricultural reclaimed water, a mixed-integer nonlinear programming model can be used to solve problems related to the allocation of reclaimed water [16]. Different configuration options can also be considered for recycled water based on the distribution of wastewater treatment plants in order to minimize costs [17]. Reclaimed water allocations are largely based on system optimization theory [18]. Water resource optimal allocation models have been developed and improved. While there has been a study similar to our work, less reclaimed water was considered in this coupled model, and the regulatory influence of reclaimed water allocation on the multi-system coupling coordination degree was not considered [19]. Therefore, the present analysis considers the impact of reclaimed water allocation options on the degree of coupling coordination and provides new ideas for reclaimed water allocations. The impact of verifying adjustments of recycled water allocation schemes on the coupling coordination degree is helpful for decision making related to urban water resource planning.

The main contributions of this work can be summarized as follows: (1) According to the coupled coordination model, we analyzed the comprehensive development level and the coupled coordination degree of each district in Suzhou. (2) A multiple regression equation for the coupling coordination degree of the WEER system and the water consumption of each effective reclaimed water pathway was established. (3) Several reclaimed water allocation schemes were formulated for the five areas of Suzhou. The most reasonable allocation scheme was determined based on the optimal coupling coordination degree. (4) The results of this study provide reference information for decision-making to promote the coordinated development of Suzhou.

2. Study area

Suzhou City is located in the central region of the Yangtze River Delta (119°55′–121°20′E, 30°47′–32°02′N), near Zhejiang, Shanghai, and other economically developed coastal provinces and cities. Suzhou takes advantage of two water systems, Taihu Lake and the Yangtze River. The total area of the municipality is 8,657.32 km^2, and there are four county-level cities in addition to downtown Suzhou. The reclaimed water usage and utilization rate in Suzhou will reach 596 million·m^3 and 51.85%, respectively, in 2025 [20]. The geographic location and distribution of Suzhou's administrative districts are shown in Fig. 2. The topography of the city is primarily plain, and the terrain elevation decreases from northwest to southeast, exhibiting the trend of a high promontory along the river. Suzhou is located in the humid climate zone in the southern part of the northern subtropics and has a subtropical humid monsoon maritime climate with four distinct seasons and abundant rainfall. In 2020, the gross regional product of Suzhou reached 201.845-billion-yuan, accounting for 19.6% of the province's

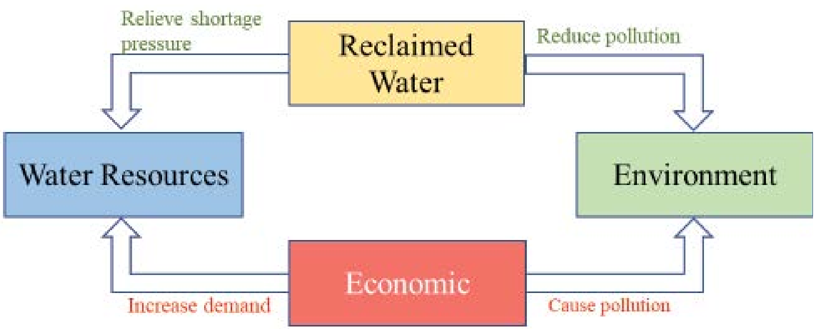

Fig. 1. System connection diagram.

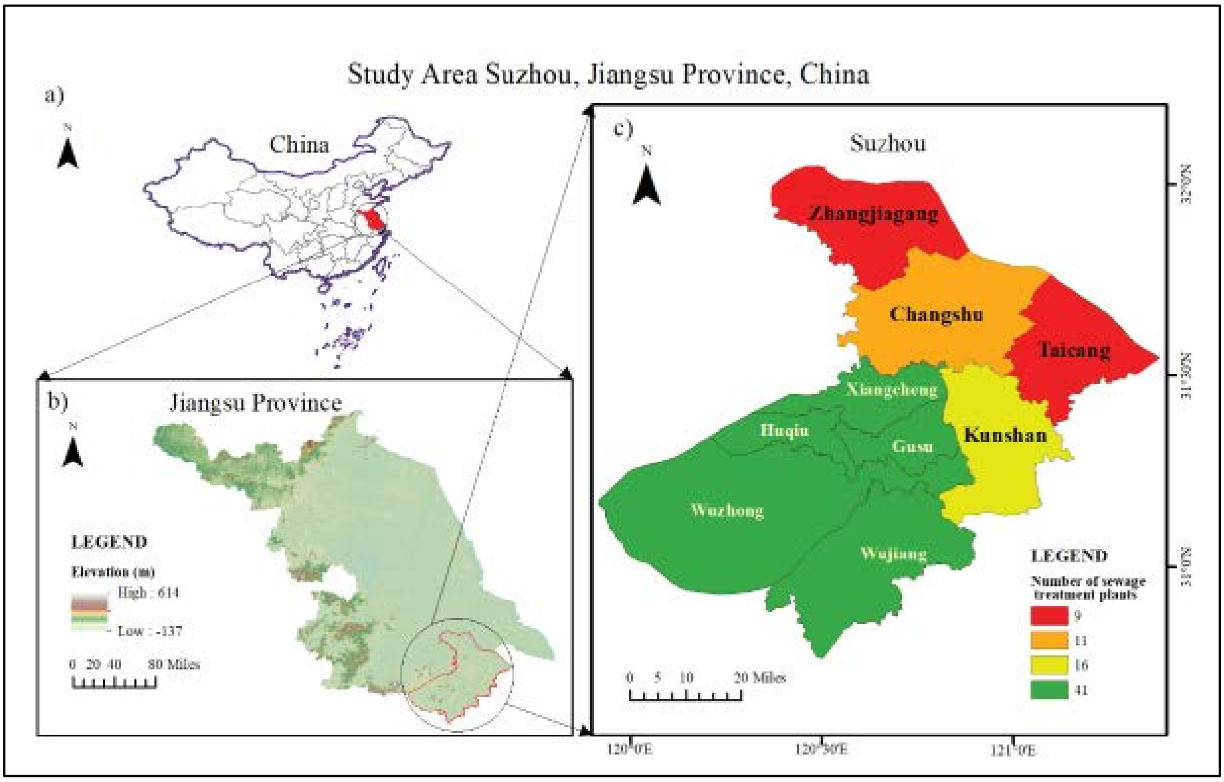

Fig. 2. (a) Map of China, (b) topographic map of Jiangsu Province, and (c) distribution map of the number of sewage treatment plants in Suzhou.

total gross regional product, and the amount of recycled water was approximately 440 million·m^3. Suzhou has 86 urban sewage treatment plants, of which 41 are in downtown Suzhou (including Wujiang, Wuzhong, Xiangcheng, Gusu, Huqiu); nine are in Zhangjiagang; 11 are in Changshu; nine are in Taicang, and 16 are in Kunshan. The overall level of development of the city's social and economic undertakings is good. However, regarding the area's socioeconomic development and water resources, there is an imbalance in the utilization and management in the various regions given the differences in water resources, the economy, the environment, and reclaimed water. Therefore, to promote the balanced and coordinated development of regional resources and the environment, it is of great practical significance to study the development of the water resources, the economy, the environment, and the recycled water system in each district of Suzhou and the degree of coupling coordination.

3. Theoretical models and methods

3.1. WEER system coupling coordination analysis method

The WEER system for the coupling coordination analysis method employed in this study is comprised of the following steps: (1) establishing an evaluation index system based on the available data; (2) standardizing the data of each index; (3) assigning weights to each index and calculating the development level; (4) establishing the WEER system coupling coordination degree model.

3.1.1. Data source and evaluation index establishment

Based on the principles of typicality, scientificity, completeness, systematicity, dynamism, and data accessibility [21–24], indices (A1–A7) provide insights into the development and utilization of water resources in the study area. Indices (B1–B6) offer a glimpse into the overall economic situation of the study area and the economic status involving the construction of ecological resources. Indices (C1–C8) reflect the ecological environment and pollution treatment situation in the study area. Finally, indices (D1–D6) shed light on the utilization of reclaimed water resources and the construction of the reclaimed water infrastructure. In this study, four subsystems—the water resources, the economy, the environment, and reclaimed water—were considered, and 27 indicators were selected to build an index system to evaluate the levels of development and coupling coordination of the WEER system in each district of Suzhou. The attributes and meanings of the indicators are listed in Table 1. The data for the indicators were obtained from the 2008–2020 Urban Construction Statistical Yearbook, the Suzhou City Water Resources Bulletin, the Suzhou Statistical Yearbook, the Suzhou National Economic and Social Development Statistical Bulletin, and Suzhou City Urban Drainage Statistics.

3.1.2. Data standardization

To eliminate the difference in the magnitude of the index data, based on the segmented linear affiliation function

Table 1
WEER system indices and meanings

Guideline system	Indicator layer	Indicator properties	Meaning
A (Water resources system)	A1 Per capita water resources (m^3)	+	The average amount of water resources per person in the region, including surface water and groundwater
	A2 Runoff coefficient	+	The ratio of the regional surface runoff to precipitation
	A3 Water consumption per ten thousand Yuan GDP (m^3)	−	The water consumption per 10,000 yuan in the region
	A4 Percentage of water used for production and operation (%)	−	The regional production and operation water consumption as a percentage of the total water consumption
	A5 Percentage of residential household water use (%)	−	The regional residential household water consumption as a percentage of the total water consumption
	A6 Per capita water supply (m^3)	+	The average water supply per person in the region
	A7 Water production module ($\times 10^4$ m^3/km^2)	+	The ratio of the total regional water resources to the total area
B (Economic system)	B1 Per capita GDP ($\times 10^4$ yuan)	+	The ratio of the regional GDP to the regional household population
	B2 Registered urban unemployment rate (%)	−	The number of registered unemployed persons in urban areas as a percentage of the total number of employed and unemployed persons in urban areas
	B3 General public budget revenue as a percentage of GDP (%)	+	The ratio of the regional general public budget revenue to the regional GDP
	B4 Disposable income per inhabitant (yuan)	+	The ratio of the resident households' discretionary income to the resident urban population
	B5 Urbanization rate (%)	+	The regional urban population as a percentage of the total resident population
	B6 Economic density ($\times 10^7$ yuan/km^2)	+	The ratio of the GDP to the total area of the region
C (Environment system)	C1 Industrial waste gas emissions per ten thousand Yuan GDP (m^3)	−	The amount of industrial waste gas emitted per 10,000 yuan in the region
	C2 Sewage treatment rate (%)	+	The percentage of regional wastewater treatment capacity vs. wastewater discharge
	C3 Sewage discharge per ten thousand Yuan GDP ($\times 10^4$ m^3)	−	The amount of sewage discharged per 10,000 yuan in the region
	C4 Greening coverage of built-up areas (%)	+	The percentage of built-up area covered by greenery in the urban built-up areas
	C5 Sludge disposal volume per ten thousand Yuan GDP (t)	+	The amount of sludge treated per 10,000 yuan in the region
	C6 Reduction of major pollutants per ten thousand Yuan GDP (t)	+	The amount of major pollutants reduced per 10,000 yuan in the region
	C7 Runoff to sewage ratio	+	The ratio of the regional surface runoff to the sewage discharge
	C8 Water quality compliance rate (%)	+	The percentage of the number of water quality standards in the water function area to the total number of water quality tests
D (Reclaimed water system)	D1 Per capita renewable water consumption (m^3)	+	The average amount of reclaimed water used per person in the region
	D2 Reclaimed water production capacity ($\times 10^4$ m^3/d)	+	The daily volume of reclaimed water generated by the reclaimed water plant
	D3 Rate of reclaimed water use (%)	+	The percentage of reclaimed water consumption for sewage treatment
	D4 Industrial water recycling rate (%)	+	The percentage of industrial repeated water consumption for industrial water consumption
	D5 Reclaimed water consumption per 10,000 Yuan GDP (m^3)	+	The amount of reclaimed water consumed per 10,000 yuan in the region
	D6 Reclaimed water pipe density (km/km^2)	+	The ratio of the length of the reclaimed water pipeline to the total area of the region

quantification method [25,26], reasonable improvements can be made in combination with the actual sample size for the situation where the index characteristic values are small. Hence, the phenomenon of data concentration after standardization can be avoided. Assuming that each indicator has three eigenvalues (i.e., the extreme difference, mean value, and excellent value), the indicator standardization method is as follows:

$$t_i(\text{Positive indicators}) = \begin{cases} 0, x_i \le a_i \\ 0.5\left(\dfrac{x_i - a_i}{b_i - a_i}\right), a_i < x_i \le b_i \\ 0.5 + 0.5\left(\dfrac{x_i - b_i}{c_i - b_i}\right), b_i < x_i \le c_i \\ 1, c_i < x_i \end{cases} \tag{1}$$

$$t_i(\text{Negative indicators}) = \begin{cases} 1, x_i \le c_i \\ 0.5 + 0.5\left(\dfrac{b_i - x_i}{b_i - c_i}\right), c_i < x_i \le b_i \\ 0.5\left(\dfrac{a_i - x_i}{a_i - b_i}\right), b_i < x_i \le a_i \\ 0, a_i < x_i \end{cases} \tag{2}$$

where a_i, b_i, and c_i are the minimal, mean, and excellent values for the ith index, respectively, and x_i is the sample data for the ith index.

The greater the negative indicator in this equation, the worse the level of development; and the greater the positive indicator, the better the level of development. To prevent the data from being affected by zero and negative values after normalization, t_i' was obtained by adding 0.000001 to the data after normalization.

3.1.3. Calculation of weights and determination of evaluation criteria for the comprehensive development level of the WEER system

There are two primary types of weight determination methods: the subjective weight determination method and the objective weight determination method. The analytic hierarchy process (AHP), as a subjective assignment method, can visually represent the relationship between the criterion level and the indicator level, but it relies too heavily on the subjective judgment of expert experience. The entropy weighting method, as an objective weighting method, has high precision for weight determination, but it ignores the interrelationships between indicators. The use of the AHP combined with the entropy weighting method can avoid the subjective and objective limitations of the individual methods and make the weighting results more reasonable and accurate.

According to the calculation processes for determining the weights using the AHP method [27,28] and the entropy weight method [29], the integrated weight of the ith index after combining the AHP and entropy weight method is expressed as w_i, and it is calculated as follows:

$$w_i = \frac{w_{i\text{I}} w_{i\text{II}}}{\sum_{i=1}^{n} w_{i\text{I}} w_{i\text{II}}} \tag{3}$$

where $w_{i\text{I}}$ is the weight of the ith indicator obtained using the AHP method; $w_{i\text{II}}$ is the weight of the ith indicator obtained using the entropy weight method, and $i = 1, 2, \ldots, n$.

The water resource development index I_W, the economic development index I_{E1}, the environmental condition index I_{E2}, and the reclaimed water development index I_R are calculated based on the results of the data standardization and weighting, and the specific calculation method has been described previously [30].

The weighted average of the development indices of the four subsystems is used to obtain the integrated development index I_{WEER} of the WEER system.

$$I_{\text{WEER}} = \alpha I_W + \beta I_{E1} + \gamma I_{E2} + \eta I_R \tag{4}$$

where α, β, γ, and η are coefficients that need to be determined, and $\alpha + \beta + \gamma + \eta = 1$.

According to the actual situation in Suzhou and the focus of this study, expert scoring was given to the four subsystems (water resources, the economy, the environment, and recycled water). On this basis, the analytic hierarchy process was used to assign weights, resulting in $\alpha = 0.39$, $\beta = 0.14$, $\gamma = 0.2$, and $\eta = 0.27$.

Similar to related work [31,32], to observe the developmental stages of the system visually, the developmental levels were divided into five stages based on the range of values of I_W, I_{E1}, I_{E2}, I_R, and I_{WEER} at an interval of 0.2 (Table 2).

3.1.4. WEER coupling coordination model

The coupling degree characterizes the strength of the interaction between the water resources, the economy, the environment, and the reclaimed water system. The degree of coupling coordination, as a measure of the synergy between subsystems [33,34], reflects the degree of coordination between the four subsystems. The higher the degree of coupling coordination, the better the coordinated development of the WEER system. In this study, the WEER system coupling degree D and coupling coordination degree C were calculated using the method of the literature [30]. The coupling coordination degree was calculated as follows:

Table 2
Classification of the development levels

Development level index	Development level stage
(0, 0.2)	Backward development stage
[0.2, 0.4]	Initial development stage
[0.4, 0.6]	Promotion development stage
[0.6, 0.8]	Good development stage
[0.8, 1]	Saturation development stage

$$C = \sqrt{D \times I_{\text{WEER}}} \quad (5)$$

where C is the coupling coordination degree of the WEER system and D is the coupling degree of the WEER system.

According to previous research results [35–37], the coupling coordination degree level can be divided into 10 levels (Table 3) to assess and judge the coordinated development of the WEER system in each district (county-level city) of Suzhou.

3.2. Multiple regression model

The various areas in Suzhou generally use recycled water for industrial water, urban miscellaneous use, plant reuse, and river landscape supplementation. According to the utilization of recycled water through each pathway for each region from 2008 to 2020 and the results derived from the coupling coordination degree, a multiple regression model was established to obtain the quantitative relationship between the coupling coordination degree and each pathway of recycled water utilization as well as to develop different recycled water allocation schemes corresponding to the optimal coupling coordination degree. Taicang uses recycled water for plant self-consumption and river and lake supplementation. It is difficult to establish the relationship between the two usages and the coupling coordination degree, but the mathematical relationship is apparent when the ratio R of the river landscape supplemental water consumption to the plant self-water consumption is introduced. The models constructed in this study using StataMP are described in Table 4; according to the results of the statistical analysis, the regression models were all valid at the 10% significance level.

3.3. Analysis of reclaimed water allocation options

There is no research demonstrating that the greater the amount of recycled water, the better the coupled coordinated development of the system in the region, and thus when setting up a recycled water allocation scheme we should consider the amount of recycled water for each usage path with different satisfaction rates. In addition, we used the information for the Suzhou reclaimed water utilization plan and water consumption quota to determine the reclaimed water demand in five areas in Suzhou; we then examined the influence of the reclaimed water consumption of each usage path under different satisfaction rates on the regional system coupling coordination.

3.3.1. Reclaimed water allocation programming

A reclaimed water allocation plan can be analyzed and formulated according to the results of the unconventional water use planning in Suzhou and the information from the Water Quota for Forestry, Animal Husbandry and Fishery, Industry, and Service Industry and Domestic Use in Jiangsu Province. At present, the effective use of recycled water in Suzhou City is primarily used for self-use, industrial water supply, municipal miscellaneous water supply, and river and lake environmental recharge, and a small amount is used for agricultural irrigation. A statistical analysis of the relevant data determined the water demand for the industry in the city's administrative districts to be 16,000 m^3/d in downtown Suzhou, 26,000 m^3/d in Zhangjiagang, 2,000 m^3/d in Changshu, and 6,000 m^3/d in Kunshan. The current annual river landscape supplemental water demand was 34.4 million·m^3/a in Changshu, 15.27 million·m^3/a in Zhangjiagang, 18.2 million·m^3/a in Taicang, 42.47 million·m^3/a in Kunshan,

Table 3
Classification of the coupling coordination levels

Coupling coordination	Coordination level	Coupling coordination	Coordination level
[0, 0.1)	Extreme disorder	[0.5, 0.6)	Near coordination
[0.1, 0.2)	Severe disorder	[0.6, 0.7)	Primary coordination
[0.2, 0.3)	Moderate disorder	[0.7, 0.8)	Moderate coordination
[0.3, 0.4)	Mild disorder	[0.8, 0.9)	Good coordination
[0.4, 0.5)	Imminent disorder	[0.9, 1)	Extreme coordination

Table 4
Regression models between reclaimed water use pathways and coupling coordination

Region	Regression model	p-value
Changshu	$y = 0.00836x_1 + 0.0014x_2 + 0.023x_3 + 0.0000811x_4 - 0.00398x_5 + 0.347$	0.09
Zhangjiagang	$y = 0.036x_1 - 0.00151x_2 - 0.0729x_3 + 0.00255x_4 - 0.00125x_5 + 0.409$	0.023
Taicang	$y = -0.000266x_1 + 0.000111x_4 + 0.0416R + 0.496$	0.034
Kunshan	$y = -0.000145x_1 - 0.0000799x_2 + 0.118x_3 + 0.0000182x_4 - 0.00023x_5 + 0.737$	0.043
Downtown Suzhou	$y = -0.0000508x_1 + 0.000149x_2 - 0.0204x_3 + 0.0000158x_4 - 0.0196x_5 + 0.812$	0.026

Note: y denotes the coupling coordination; x_1, x_2, x_3, x_4, and x_5 denote the amount of water used for plant self-water consumption, industrial water consumption, urban miscellaneous water consumption, river landscape replenishment, and other means of water use, respectively. R denotes the ratio of the river landscape supplemental water consumption to the plant self-water consumption.

and 262.47 million·m^3/a in downtown Suzhou. Analysis of the statistics for the study period revealed that the proportion of the total use of recycled water in the area accounted for by the plant's water was 25% in downtown Suzhou, 0.16% in Zhangjiagang, 0.3% in Changshu, 3% in Kunshan, and 25% in Taicang. For the municipal miscellaneous road washing water, the general value of 2 L/(m^2·d) and the annual washing according to 235 d (because the average annual number of days with precipitation in the last 10 y was about 130 d) were utilized. For the urban greening water, the general value of 0.5 m^3/(m^2·a) was utilized, along with 10 L/(person·times) for toilet flushing water. For other water uses such as agricultural irrigation, the value of 60 m^3/mu was utilized. At present, there remain differences in the actual uses of recycled water in the various districts (county-level cities) in Suzhou. For example, Taicang used recycled water for plant self-use and river landscape supplementation, while downtown Suzhou used the water for plant self-use, industrial water, urban miscellaneous use, and river landscape supplementation. Therefore, combined with the actual use of reclaimed water in Suzhou and the potential use level, the total annual reclaimed water demand was calculated to be 35.79 million·m^3 in Changshu, 3.858 million·m^3 in Zhangjiagang, 24.27 million·m^3 in Taicang, 65.71 million·m^3 in Kunshan, and 359.2 million·m^3 in downtown Suzhou.

According to the estimated water demand values for the different utilization paths in each administrative region and according to the principle of 50%, 75%, 95%, and 100% of the total recycled water demand to meet the principle, a supply and demand balance analysis and evaluation of the WEER system coupling coordination the recycled water utilization configuration scheme was conducted. The proposed specific configuration scheme is described in Table 5.

3.3.2. Reclaimed water supply and demand balance

Suzhou City has 86 urban sewage treatment plants built to a scale of 4.2 million·m^3/d. The downtown Suzhou area has 41 plants, with a total sewage treatment capacity of 2,357,500 m^3/d; Zhangjiagang has 9 plants, with a total sewage treatment capacity of 285,000 m^3/d; Changshu has 11 plants, with a total sewage treatment capacity of 402,000 m^3/d; Taicang has 9 plants, with a total sewage treatment capacity of 285,000 m^3/d; and Kunshan has 16 plants, with a total sewage treatment capacity of 872,000 m^3/d. Suzhou plans to achieve more than 50% utilization of recycled water. According to the sewage treatment capacity of the city's major sewage treatment plants and the related planning requirements, the scale of the recycled water supply in each district and county-level city can be reached as follows: 430.24 million·m^3 in downtown Suzhou, 52.01 million·m^3 in Zhangjiagang, 73.36 million·m^3 in Changshu, 52.01 million·m^3 in Taicang, and 159.14 million·m^3 in Kunshan. The aforementioned estimated demand for recycled water in Suzhou indicates that the water supply is much greater than the water demand. Therefore, each configuration scheme listed in Table 5 can balance the recycled water supply and demand and is reasonable.

Table 5
Suzhou recycled water use configuration program

Region	Satisfaction rate	Plant self-water consumption (×10^4 m^3)	Industrial water consumption (×10^4 m^3)	Urban miscellaneous water consumption (×10^4 m^3)	River landscape supplemental water consumption (×10^4 m^3)	Others (×10^4 m^3)	Total (×10^4 m^3)
Changshu	50%	5.33	36.67	0.89	1,720	26.67	1,789.56
	75%	8	55	1.34	2,580	40	2,684.34
	95%	10.13	69.67	1.7	3,268	50.67	3,400.16
	100%	11	73	2	3,440	53	3,579
Zhangjiagang	50%	3	483.33	4.83	763.33	674.67	1,929.17
	75%	4.5	725	7.25	1,145	1,012	2,893.75
	95%	5.7	918.33	9.18	1,450.33	1,281.87	3,665.42
	100%	6	967	10	1,527	1,349	3,858
Taicang	50%	303.33	0	0	910	0	1,213.33
	75%	455	0	0	1,365	0	1,820
	95%	576.33	0	0	1,729	0	2,305.33
	100%	607	0	0	1,820	0	2,427
Kunshan	50%	100	106.67	2.33	2,123.33	953.33	3,285.67
	75%	150	160	3.5	3,185	1,430	4,928.5
	95%	190	202.67	4.43	4,034.33	1,811.33	6,242.77
	100%	200	213	5	4,247	1,907	6,571
Downtown Suzhou	50%	4,546.67	286.67	3.33	13,123.33	0	17,960
	75%	6,820	430	5	19,685	0	26,940
	95%	8,638.67	544.67	6.33	24,934.33	0	34,124
	100%	9,093	573	7	26,247	0	35,920

4. Results

4.1. Correlation analysis of indicators

To verify the existence of relationships between the selected indicators, the data for downtown Suzhou were analyzed using a Spearman correlation coefficient matrix. The correlation network diagram between the 27 indicators is shown in Fig. 3. The meanings of the indicator numbers are listed in Table 1. As shown in Fig. 2, there are different degrees of correlation among the indicators, and some of the indicators have strong correlations with up to 16 other indicators. The proportion of positive correlations among the indicators was higher. The water resources system indicator A3 (water consumption per ten thousand Yuan GDP) was significantly positively correlated with B2 (registered urban unemployment rate), C3 (sewage discharge per ten thousand Yuan GDP), C5 (sludge disposal volume per ten thousand Yuan GDP), and C6 (reduction of major pollutants per ten thousand Yuan GDP). Furthermore, A3 was significantly negatively correlated with other indicators of the economic system, including C1 (industrial waste gas emissions per ten thousand Yuan GDP), C2 (sewage treatment rate), C8 (water quality compliance rate), D2 (reclaimed water production capacity), and D6 (reclaimed water pipe density). A1 (per capita water resources) was significantly positively correlated with A2 (runoff coefficient), A7 (water production modulus), and C7 (runoff to sewage ratio). Two indicators exhibited a strong positive correlation, with similar correlations to the other indicators. Two indicators exhibited negative correlations, with opposite correlations to other indicators. In general, the subsystems were interrelated, and the indicators were closely linked. The higher the positive economic indicators, the higher the demand for water resources, and the higher the level of environmental pollution. Simultaneously, the lower the amount of water resources, the higher the level of development and use of recycled water. The index system constructed in this study has been tested and analyzed in terms of its completeness, objectivity, and representativeness, and it is generally reasonable.

4.2. Analysis of development level

The development of the WEER system (expressed as I_{WEER}) in each region of Suzhou from 2008 to 2020 (13 y in total) is shown in a box plot in Fig. 4. The upper and lower boundaries of the rectangles indicate the upper and lower quartiles of the index, respectively. The horizontal line in the rectangle indicates the median. The hollow point indicates the mean value and the solid point indicates an outlier. The upper and lower edges of the box indicate the extreme and minimum values of the box, and the maximum values of the subsystem development index set in each region in all years are marked in the figure. From the figure, (1) the changes in the development of the four subsystems vary considerably, with the most pronounced changes in the development of the water resources and the least changes in the economic development over the past 13 y. The vast majority of the median lines in the graph are above the mean point, indicating that the development of most of the regional systems was above average during the study period. (2) Downtown Suzhou had the highest degree of recycled water development and utilization, while Zhangjiagang and Taicang had

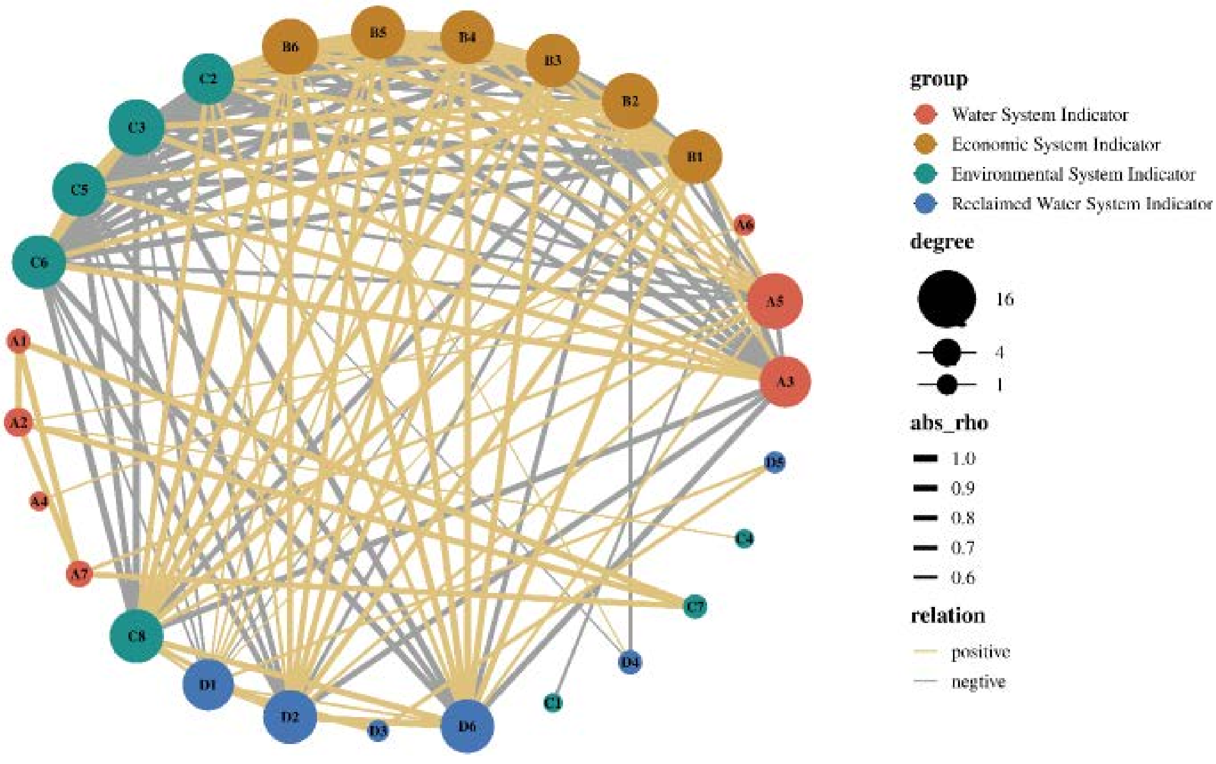

Fig. 3. Correlation network diagram of evaluation indicators.

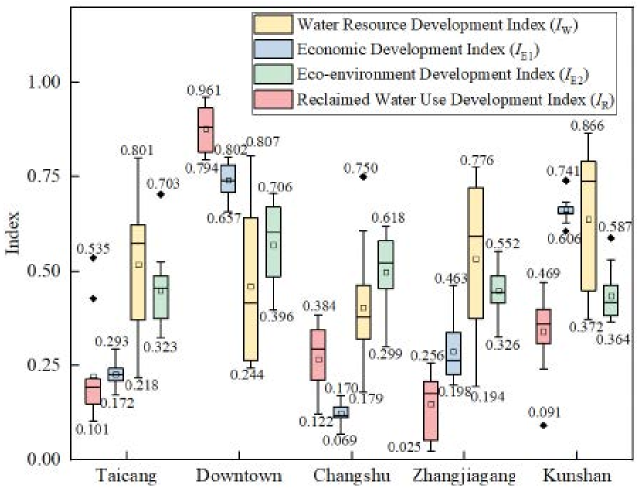

Fig. 4. Box plot of the development level index of each subsystem of the WEER system in Suzhou.

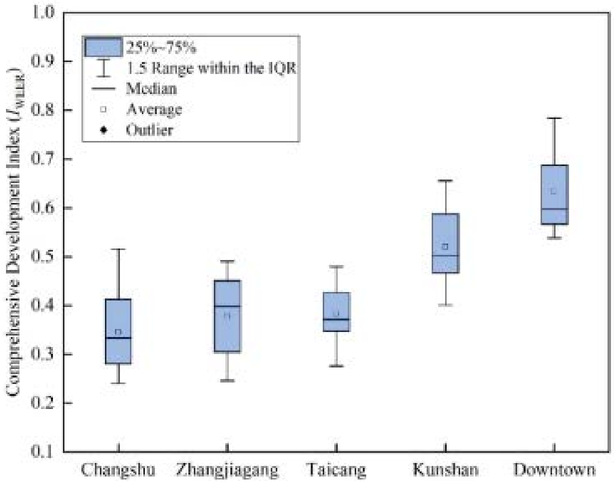

Fig. 5. Box plot of the comprehensive development level of the WEER system in Suzhou.

the corresponding lowest values. Given the actual distribution of the wastewater treatment plants in Suzhou, the wastewater treatment capacity has a greater impact on changes in the development of reclaimed water in the city. (3) Downtown Suzhou was far ahead of other regions in terms of socio-economic development, with various indicators steadily improving, while Changshu had the lowest level of economic development, followed by Taicang. The differences were reflected in indicators such as the per capita GDP and urbanization rate. (4) The greatest degree of change was in water use development over the 13 y, implying that urban development clearly influenced the magnitude of the growth of the water demand. (5) The ecological level was not very different among the five regions of Suzhou; however, an analysis of the calculation results shows that the lower the economic level of the same region, the better the local ecological level, suggesting that economic and ecological development do not go hand in hand. (6) Within each index set, the significant anomalies were concentrated in two areas, Taicang and Kunshan. Taicang had a high recycled water utilization rate and per capita recycled water use in the first 2 y of the study period that resulted in the degree of recycled water development remaining in the development enhancement stage during the study period, but it did not continue to maintain this development trend. In terms of the ecological environment, the degree of pollutant treatment in Taicang had increased by 2020, and it entered a good stage of development with significant progress in that year. The socioeconomic development of Kunshan changed greatly between 2008 and 2020 compared to other years, but it always remained in a good stage of development with a solid economic foundation. The steep decline in the use of recycled water in Kunshan in 2011 caused the level of recycled water development and utilization to decline in that year, while the sudden increase in the runoff ratio in Kunshan in 2009 had a better impact on the ecological environment in that year.

The variation characteristics of the WEER system integrated development index for each district (county-level city) in Suzhou are shown in Fig. 5. As the chart shows, downtown Suzhou led the overall development level, followed by Kunshan. No abnormal values appeared in any of the regions, and the differences between the mean points and the median were within 0.04, indicating that the comprehensive development level of the five regions was relatively stable. It also shows that the closer the location of the area was to the city, the better the integrated development. The comprehensive development levels of Changshu, Zhangjiagang, and Taicang were not very different, and none of them reached a good stage of development. The reclaimed water utilization and economic development in these three regions evidently lagged behind those in the other regions, a situation that led to the low development level of these three regions and also reflected the importance of the degree of reclaimed water utilization for regional economic development.

4.3. Analysis of WEER system coupling coordination

The changes in the WEER system coupling coordination for each district (county-level city) in Suzhou from 2008 to 2020 were calculated using the coupling coordination degree model and are shown in Fig. 6. The change in the coupling coherence across the regions was similar to the trend of integrated development. (1) The median degree of coupling coordination of the WEER system in all five regions was less than the average, indicating that the average was close to a high degree of coordination, and the future development of the coordination in the regions will improve. (2) Changshu and Zhangjiagang were on the verge of dislocation in individual years, and none of the five regional systems were coupled with quality coordination. There is still significant potential for coordinated development. (3) Downtown Suzhou had the best coupling coordination, mostly with an intermediate level of coordination and good coordination. When the areas were far from downtown Suzhou, the natural resource base was weaker, and these areas exhibited stagnation of the coupling coordination development.

4.4. Rational allocation of regional reclaimed water based on the coupling coordination criterion

The coupling coordination corresponding to the different satisfaction rate schemes according to the multiple regression model and the reclaimed water allocation schemes is shown in Fig. 7. In Suzhou, the higher the rate of recycled water supply satisfaction, the higher the coordination of the WEER system coupling in the area, except for downtown Suzhou. The changes in the satisfaction rate of the recycled water supply in Taicang had the least positive impact on the coupling coordination of the WEER system. The degree of impact was inconsistent among all of the regions; however, the overall use of recycled water promoted the coupled and coordinated development of the WEER system in the region. In addition, the best coupled coordinated degree corresponded to the configuration scheme under 100% satisfaction of the water supply rate in the four regions, except for downtown Suzhou. To investigate the reason why the higher reclaimed water satisfaction rate in downtown Suzhou caused the coordination degree to decrease, we set up alternative scenarios for downtown Suzhou. The other water demand base amount was set to zero, and thus it was not considered. This scheme was based on meeting 50% of the recycled water demand and changing the rate of meeting the water demand of each utilization pathway (Table 6). Scenario I represented the base scenario that met 50% of the reclaimed water demand for each use. Scenario II represented an adjustment of the plant self-water consumption satisfaction rate to 75% of the base scenario. In Scenario III the industrial water consumption satisfaction rate was adjusted to 75% compared to the base case. Scenario IV represented an adjustment of only the urban miscellaneous water consumption satisfaction rate to 75% compared to the base scenario. In Scenario V, the satisfaction rate of the river landscape supplemental water consumption was adjusted to 75% compared to the base scenario.

The coordination of each coupling for the alternate scenario of reclaimed water allocation in downtown Suzhou is shown in Table 7. Based on Table 7 and Fig. 7, the highest coupling coordination of the system would be achieved when a 50% satisfaction rate is set for the use of each downtown reclaimed water use pathway. When only the plant self-water consumption or only the urban miscellaneous

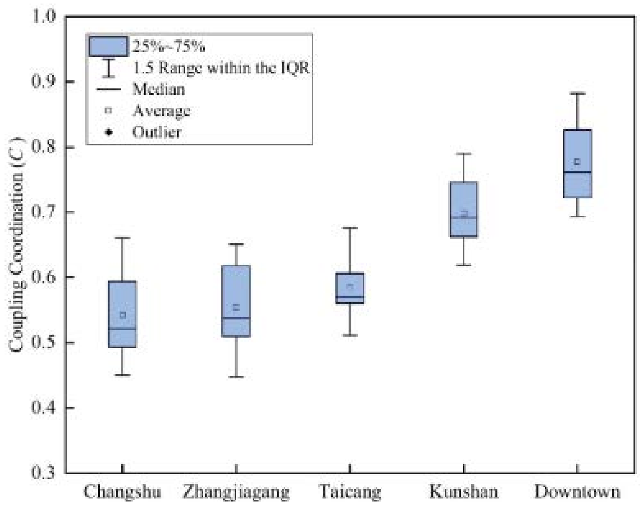

Fig. 6. Box plot of WEER system coupling coordination in Suzhou.

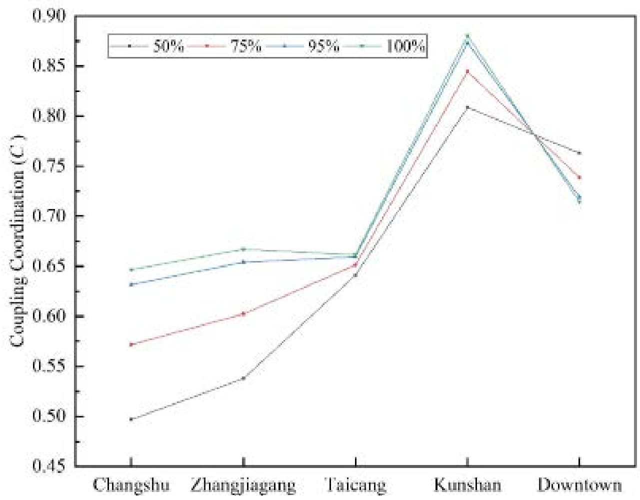

Fig. 7. Coupling coordination of the reclaimed water allocation schemes in Suzhou.

Table 7
Coupling coordination corresponding to alternate scenarios of the reclaimed water allocation in downtown Suzhou

Scheme	I	II	III	IV	V
Coupling coordination	0.763	0.648	0.784	0.729	0.866

Table 6
Downtown Suzhou reclaimed water allocation backup plan

Utilization path	Satisfaction rate				
	I	II	III	IV	V
Plant self-water consumption	50%	75%	50%	50%	50%
Industrial water consumption	50%	50%	75%	50%	50%
Urban miscellaneous water consumption	50%	50%	50%	75%	50%
River landscape supplemental water consumption	50%	50%	50%	50%	75%

water consumption is increased, the coupling coordination of the WEER system in the urban area decreases; and when only the industrial water consumption or only the river landscape supplemental water consumption is increased, the coupling coordination of the downtown Suzhou WEER system increases, and the positive impact of the river landscape supplemental water is the greatest. As the most economically developed area, downtown Suzhou has experienced rapid industrial development, resulting in a huge demand for industrial water. In addition, the river network in downtown Suzhou is extensive, but the rivers generally have insufficient hydrodynamic power and poor water flow, and thus there is a large demand for river landscape replenishment. When increasing the amount of recycled water for each use by the same proportion, the negative effect of the plant self-water consumption and urban miscellaneous water consumption on the system coupling coordination is greater than the positive effect of the industrial water consumption and river landscape replenishment, resulting in a reduced system coupling coordination for downtown Suzhou. In summary, the most important means of regulating the coupling and coordination of the system in downtown Suzhou would be to increase the river landscape supplemental water consumption.

5. Discussion

In this paper, we utilized panel data from 2008 to 2020 for each district (county-level city) in Suzhou to develop a model of the WEER system's coupling coordination degree in each district (county-level city) in Suzhou using the AHP-entropy weighting method to determine the weights. Accordingly, a multiple regression equation was established between the coupling coordination degree of the WEER system and the consumption of reclaimed water via each pathway. In addition, several reclaimed water allocation schemes were formulated for the five areas in Suzhou, and the most reasonable allocation scheme was determined based on the best coupling coordination degree. In conclusion, our research comprehensively explored the four subsystems of water resources, economy, environment, and reclaimed water and proposed the concept of the urban WEER system, offering a new perspective on the coupling relationship between urban agglomeration, urbanization, and reclaimed water. The methods and conclusions of this study can serve as valuable references for researching the coupling and coordinated development of the WEER system in other urban areas in China.

The study reveals that the coupling and coordination of the WEER system and the overall development level of the economic center area fall within the middle to upper range. This trend aligns with findings from other related system coupling studies [36,38]. likely due to the unique developmental characteristics of these areas. Downtown and provincial capital cities tend to be highly urbanized, experiencing have rapid economic development and demanding various resources. A better economic foundation is also favorable for the construction of environmental improvement facilities. This point of view can also be applied to the coupling and coordination development trends of the WEER system in other cities. Additionally, this study explores the impact of adjusting the reclaimed water allocation scheme in the region, a research direction that has received limited attention. However, using renewable water has been proven to drive future economic development in cities [19]. Recycled water utilization can alleviate the lack of water resources in Suzhou City, while reducing the pollution of the water environment. Therefore, optimization of reclaimed water allocation options can be a strategic step toward promoting integrated urban development.

There are some limitations to this study. Given its focus on the specific situations of the water resources, economy, ecological environment, and recycled water in five regions of Suzhou, it may not be representative of all cities. In future research, expanding the study's scope to improve the model, and research ideas with more comprehensive data information could be used to verify the universality of the idea that reclaimed water utilization can regulate the coupling coordination of urban WEER systems.

6. Conclusions

The analysis results showed that downtown Suzhou had the best results regarding the excellent performance of each system development and the WEER system coupling coordination. The closer the other areas were geographically to downtown Suzhou, the better the area performed. As a typical city with a developed economy in southern China, Suzhou has a large demand for water resources. The substantial future development potential of the recycled water industry can effectively promote the efficient use of water resources, the development of a green economy, and the sustainable development of the ecological environment. In addition, the Ministry of Water Resources, in conjunction with other relevant departments, has stressed that several cities need to actively carry out configuration pilot work in typical areas of recycled water use. Strong policy support can effectively promote the use of recycled water [39]. The development of this region should be government-led and market-driven, with environmental protection as the primary premise for allocating regional water resources, optimizing industrial institutions, promoting economic quality and efficiency, and encouraging the use of renewable water resources.

Unlike in previous studies, the aim of the proposed rational allocation of reclaimed water was to achieve the best-coupled coordination degree of the development of the regional systems as well as to balance the water supply and demand. The results of this study also demonstrated that different recycled water allocation schemes could affect the coordination of regional development. Under the condition of complete hardware facilities and a solid economic foundation, the greater the amount of recycled water used by the four county-level cities in Suzhou, the more fully utilized it would be in various ways. In addition, downtown Suzhou should not pursue an increase in the total amount of recycled water use but rather should use the recycled water more fully to supplement water consumption for the river and lake landscapes. This would lead to better coordination of the WEER system in the five regions of Suzhou.

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