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Study on the Rational Allocation of Regional Reclaimed Water Based on the System Coupling Coordination Criterion

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Objectives

- Take five areas (the downtown Suzhou and four county-level cities) in Suzhou as the study area and measure the development of urban water resources, the economy, the environment, and reclaimed water in all aspects.
- Establish the water resources-economic-environment-reclaimed water (WEER) system coupling coordination model that meets the actual situation of the study area.
- Study the impacts of different reclaimed water allocation schemes on the coupling coordination of the urban WEER system.

Methods

Table 1. WEER system indexes

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 versus 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

Coupling Coordination Model

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

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

$$W_i = \frac{W_{it} W_{iII}}{\sum_{i=1}^{n} W_{it} W_{iII}}$$

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

$$D = \left\{ \frac{I_W \times I_{E1} \times I_{E2} \times I_R}{\left[\frac{(I_W + I_{E1} + I_{E2} + I_R)}{4}\right]^4} \right\}^{\frac{1}{4}}$$

$$C = \sqrt{D \times I_{WEER}}$$

The water resources-economic-environment-reclaimed water (WEER) system coupling coordination degree

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The utilization of recycled water through each pathway for each region from 2008 to 2020

Table 2. 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

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 in it.

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Table 3. Suzhou recycled water use configuration program

Region	Satisfaction rate	Plant self-water consumption ($\times 10^4$ m^3)	Industrial water consumption ($\times 10^4$ m^3)	Urban miscellaneous water consumption ($\times 10^4$ m^3)	River landscape supplemental water consumption ($\times 10^4$ m^3)	Others ($\times 10^4$ m^3)	Total ($\times 10^4$ m^3)
Changshu	50%	5.33	36.67	0.89	1720	26.67	1789.56
	75%	8	55	1.34	2580	40	2684.34
	95%	10.13	69.67	1.7	3268	50.67	3400.16
	100%	11	73	2	3440	53	3579
Zhangjiagang	50%	3	483.33	4.83	763.33	674.67	1929.17
	75%	4.5	725	7.25	1145	1012	2893.75
	95%	5.7	918.33	9.18	1450.33	1281.87	3665.42
	100%	6	967	10	1527	1349	3858
Taicang	50%	303.33	0	0	910	0	1213.33
	75%	455	0	0	1365	0	1820
	95%	576.33	0	0	1729	0	2305.33
	100%	607	0	0	1820	0	2427
Kunshan	50%	100	106.67	2.33	2123.33	953.33	3285.67
	75%	150	160	3.5	3185	1430	4928.5
	95%	190	202.67	4.43	4034.33	1811.33	6242.77
	100%	200	213	5	4247	1907	6571
Downtown Suzhou	50%	4546.67	286.67	3.33	13123.33	0	17960
	75%	6820	430	5	19685	0	26940
	95%	8638.67	544.67	6.33	24934.33	0	34124
	100%	9093	573	7	26247	0	35920

The best coupling coordination degree corresponding to alternate scenarios of reclaimed water allocation

Results

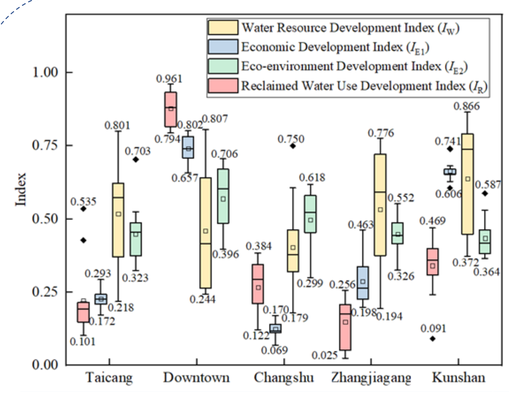

Figure 1. Box plot of the development level index of each subsystem of the WEER system in Suzhou

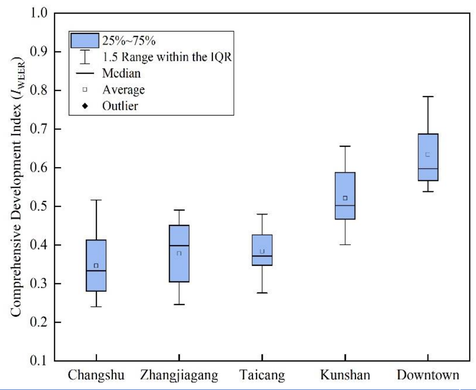

Figure 2. Box plot of the comprehensive development level of the WEER system in Suzhou

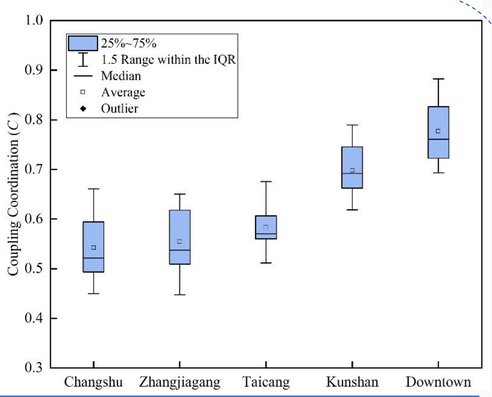

Figure 3. Box plot of WEER system coupling coordination in Suzhou

Conclusions

- In the excellent performance of each system development and the WEER system coupling coordination, downtown Suzhou had the best results.
- The closer the other areas were geographically to downtown Suzhou, the better the area performed.
- The development of this region should be government-led and market-driven with environmental protection as the primary premise to scientifically allocate regional water resources, optimize industrial institutions, promote economic quality and efficiency changes, and encourage the use of renewable water resources.
- Downtown Suzhou needs to use the recycled water more fully to supplement water consumption for the river and lake landscapes.
- Different recycled water allocation schemes could change the coordination of regional development. Since this study focused on the specific situation of the water resources, economy, ecological environment, and recycled water in five regions of Suzhou, it presented clear relevance. In future research, the scope of the study could be expanded to improve the model, and research ideas with more comprehensive data information could be used to obtain the universality of the view that the utilization of reclaimed water can regulate the coupling coordination of the urban WEER system.

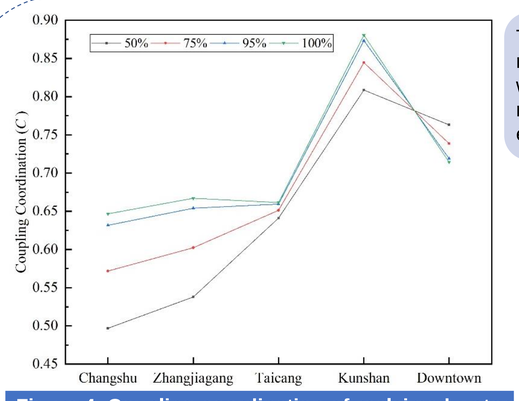

Figure 4. Coupling coordination of reclaimed water allocation schemes in Suzhou

The best coupled coordinated degree corresponded to the configuration scheme under 100% satisfaction of the water supply rate in four regions, except downtown Suzhou.

To investigate the reason why the higher reclaimed water satisfaction rate in downtown Suzhou makes the coordination degree decrease, we set up alternative scenarios for downtown. The other water demand base amount was set as 0, and it was not considered. This scheme is based on meeting 50% of the recycled water demand and changing the rate of meeting the water demand of each utilization pathway.

Table 4. Downtown Suzhou reclaimed water allocation backup plan

	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%

Table 5. Coupling coordination corresponding to alternate scenarios of reclaimed water allocation in downtown Suzhou

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

The most important means of regulating the coupling and coordination of the system in downtown Suzhou is to increase the river landscape supplemental water consumption.

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