

# Evaluation of the effect of regional collaborative management of water pollution in Nanjing-Zhenjiang-Yangzhou metropolitan area based on grey theory

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**Abstract-** This paper mainly focuses on the current situation of collaborative water pollution management in the Nanjing-Zhenjiang-Yangzhou Region metropolitan area. For this purpose, a synthetical, innovative and more comprehensive indicator system, based on PSR theory and the degree of regional synergy, which is also suitable for further evaluations towards regional collaborative water pollution management, was constructed by analyzing the existing theories and programs of collaborative regional management. The indicator weights are determined by fuzzy hierarchical analysis. The current situation of water pollution cooperative management in Nanjing-Zhenjiang-Yangzhou metropolitan area is evaluated as good with a probability of 0.9453 in the third grey class by a grey clustering model combining the data from the annual environmental bulletin of the Environmental Protection Bureau of the three cities and 2018 Nanjing Yearbook etc. Finally, several policy suggestions are given.

## 1 Introduction

The synergistic management of water pollution in the Nanjing-Zhenjiang-Yangzhou metropolitan region is an important element in the construction of ecological civilization in the Yangtze River Delta basin, and the study of the synergistic management scheme in the region with respect to the water quality characteristics of the Nanjing-Zhenjiang-Yangzhou metropolitan area is an important initiative to protect the ecological environment and manage water pollution in the Yangtze River Delta basin. At the same time, the integration of Nanjing-Zhenjiang-Yangzhou is a major strategic deployment of Jiangsu Province, and it is of great economic benefit to research how to collaboratively manage water pollution in the whole Nanjing-Zhenjiang-Yangzhou metropolitan area with the advantage of Nanjing, which is a mega-city of Nanjing-Zhenjiang-Yangzhou region, so as to promote the synergistic development of the whole Nanjing-Zhenjiang-Yangzhou metropolitan area.

## 2 Determination of evaluation Indicator

In order to determine the evaluation index system in a more comprehensive, concise and representative way, and to focus on the evaluation of regional collaborative governance performance, we determine the Nanjing-Zhenjiang-Yangzhou regional collaborative governance model [1] as interactive and consultative based on the

judgment that the degree of regional integration of Nanjing-Zhenjiang-Yangzhou is still in the initial promotion period [2]. Therefore, in the process of collaborative governance, the degree of regional synergy is more critical and is listed as a positive indicator.

**Table I.** Regional Collaborative Governance Model

		Asymmetry of resource dependency	
		Strong	Weak
The urgency of cross-domain governance	Strong	Authority Driven	Authoritative coordination
	Weak	Lead and follow-up	Interactive consultation

As well as the available literature research results as shown in the table, the Delphi method was used to investigate and obtain the index system for assessing the collaborative governance of watersheds, as shown in the table below.

**Table II.** Regional Collaborative Governance Theories Relevant

Literature	Related factors
Yang Z, Niu G.M <sup>[3]</sup>	Legal regulations of unified watersheds, basic principles of establishing cross-regional ecological compensation mechanisms, compensation standards, multiple subjects and joint measures
Zhang J.T <sup>[4]</sup>	The impact of contradiction and conflict between government regulation scenarios and regional synergy scenarios in water pollution management on the

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	effectiveness of governance
Yang H.S, Zhou X.Y <sup>[1]</sup>	The impact of the lack of strong administrative authority and enforcement effectiveness on the effectiveness of collaborative management when local government departments such as water conservancy and environmental protection discuss issues such as water pollution prevention and control
Liu H <sup>[5]</sup>	The link between tertiary industry output and water environment quality
Ma T <sup>[6]</sup>	Evaluate the government's performance in water pollution control from three aspects: function, effectiveness and potential, and break down indicators such as the satisfaction rate of complaint handling
Zhu J.Q <sup>[7]</sup>	Applying the PSR model to the collaborative management evaluation model, the model can relatively scientifically explain the relationship between the three dimensions of pressure, state and response in the collaborative management of water pollution in Nanjing-Zhenjiang-Yangzhou

Chen X.M <sup>[8]</sup>	Evaluate pollution management performance with capital investment in synergistic watershed water resources management as an input indicator and economic development as an output indicator
Xiang X <sup>[9]</sup>	Using regional economic growth and natural environment protection as ecological civilization evaluation indicators
Han L <sup>[2]</sup>	Analysis of the current status of Nanjing-Zhenjiang-Yangzhou integration from the perspective of the degree of economic ties, the degree of industrial synergy and the degree of market integration shows that the integration is still at the preliminary stage of cooperation

Synthesizing the findings of the above literature on regional collaborative governance model with the relevant theories of PSR model, we give the following indicators system.

**Table III.** Evaluation Indicator System of Watershed Collaborative governance<sup>a, b</sup>

Indicator Category	Tier 1 Indicators	Secondary indicators	Nanjing	Zhenjiang	Yangzhou	Nature of Indicator
Pressure Indicators	Water environment evaluation index P1	Amount of ammonia nitrogen in wastewater (million tons) P11	0.77	0.66*	0.56	Reverse
		Chemical oxygen demand in wastewater (million tons) P12	5.99	5.07*	4.14	Reverse
		Industrial wastewater discharge (billion tons) P13	1.55	0.55	0.57	Reverse
Status Indicators	Regional related economic indicators S1	GDP per capita (yuan) S11	383424	534831	260421	Positive
		Gross domestic product of tertiary industry (billion yuan) S12	7825.00	2,102.35	2408.38	Positive
Response Indicators	Government Effectiveness Indicator R1	Municipal wastewater treatment rate R11	96.5%	93.8%	87.0%	Positive
		Surface water functional area water quality standard attainment rate R12	81.8%	100%	93.8%	Positive
		Sudden water pollution incidents (pieces) R13	11	0	4	Reverse
		Centralized drinking water source water quality compliance rate R14	100%	100%	100%	Positive
	Government Function Indicator R2	Existence of Water Environment Quality Report R21	Yes	Yes	Yes	Positive
		Number of environmental administrative penalty cases R22	1993	809	1261	Positive
		Existence of emissions trading mechanism R23	Yes	No	Yes	Positive
		Comprehensive Complaint Resolution Rate R24	99.7%	100%	100%	Positive
		Complaint handling satisfaction rate R25	91.3%	85.6%	87.3%	Positive
		Ecological compensation for water environment R26	Yes	No	Yes	Positive
	Regional Synergy Indicator R3	Number of joint party and government meetings in 5 years R31	2			Positive
		Number of articles published in regional dailies related to Nanjing-Zhenjiang-Yangzhou integration in 5 years R32	8			Positive
		Uniform degree of pollutant emission standards R33	More uniform			Positive

Potential Indicators	Water pollution control potential indicators Q1	Number of major environmental research projects Q11	22	13	2	Positive
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A. Pollutant emission standards in the three cities are based on the emission standards of Jiangsu Province, with modifications to individual regulations.

B. Secondary indicator data are from *Nanjing Yearbook*, *Zhenjiang Yearbook*, *Yangzhou Yearbook*, *Nanjing Statistical Yearbook*, *Zhenjiang Statistical Yearbook*, *Yangzhou Statistical Yearbook* of 2018 and the annual environmental bulletin of the Environmental Protection Bureau of the three cities of Nanjing, Zhenjiang and Yangzhou. R31 and R32 are from the knowledge network daily library and search engine search, individual missing data are replaced with the average value of similar data from the other two cities.

### 3 Evaluation model construction of regional collaborative water pollution management in Nanjing-Zhenjiang-Yangzhou metropolitan area

#### 3.1 Regional Synergy Indicator Evaluation Rating Determination

Before the construction, there are several assumptions is about to set.

Let

$A_{ij}$ : decision value of quantitative indicator  $i$  in case  $j$

$x_{ij}$ : decision value of quantitative indicator  $i$  in city  $j$

$W_{jk}$ : weight of  $k$ -index for city  $j$

$r_{ij}$ : indicates the affiliation of the importance of factor

$I_i$  over factor  $I_j$ .

$w_i$ : weight of indicator  $i$

The regional synergy index R3 is a qualitative index to reflect the degree of concern, coordination and rigor of the synergistic governance of the three cities of Nanjing-Zhenjiang-Yangzhou from the public information. In order to quantitatively analyze the degree of influence of each factor on the target, the qualitative indicators are divided into 10 levels of influence, with values ranging from integer 0 to 10 points, corresponding to levels 1, 2, .....10, respectively. The higher the level indicates the better evaluation obtained by the corresponding indicator data.

Based on the defined measurement values and indicator evaluation system, three evaluators were asked to assign values to the strengths and weaknesses of qualitative indicators  $A_{ij}$  based on available data, and the scores were obtained as shown in the table below.

**Table IV.** Expert scoring results of qualitative indicators

Indicators	Exper1	Exper2	Exper3
Number of joint party and government meetings in 5 years R31	4	4	3
Number of articles published in regional dailies related to Nanjing-Zhenjiang-Yangzhou integration in 5 years R32	4	5	2
Uniform degree of pollutant emission standards R33	7	8	6

#### 3.2 Construction of the sample matrix

To prevent subjectivization of quantitative indicators, this paper only considers the existing government public data of indicators as the input matrix for the sample matrix construction of quantitative indicators.

##### 3.2.1 Dimensionless sample data

The gray variable weight clustering is applicable to the case where the meaning and the scale of indicators are the same. The various influencing factors of each cluster indicators of different levels in the water pollution control may cause inaccurate evaluation results [10]. Thus, it is necessary to proceed the dimensionless processing. Considering the feasibility of data processing, this paper adopts the maximization formula for the positive indicators and the inverse formula for the negative indicators, so that the direction of the indicators is unified after dimensionless processing.

Letting the normalized matrix be  $\bar{X} = [\bar{x}_{ij}]_{n \times m}$ , the formula for normalizing the maximum value of the positive indicator  $x_{ij}$  is

$$\bar{x}_{ij} = \frac{x_{ij}}{M_j} \quad (1)$$

The inverse normalized formula for the inverse indicator  $x_{ij}$  is

$$\bar{x}_{ij} = \frac{M_j - x_{ij}}{M_j - m_j} \quad (2)$$

Among them,  $M_j = \max_i x_{ij}$ ,  $m_j = \min_i x_{ij}$ ,  $\bar{x}_{ij} \in [0, 1], i = 1, 2, \dots, n, j = 1, 2, \dots, m$ .

The dimensionless sample matrix can be obtained

$$\bar{X} = \begin{bmatrix} 0.0000 & 0.5238 & 1.0000 \\ 0.0000 & 0.4973 & 1.0000 \\ 0.0000 & 1.0000 & 0.9800 \\ 0.7169 & 1.0000 & 0.4869 \\ 1.0000 & 0.2687 & 0.3078 \\ 1.0000 & 0.9720 & 0.9016 \\ 0.8180 & 1.0000 & 0.9380 \\ 0.0000 & 1.0000 & 0.6364 \\ 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 \\ 1.0000 & 0.4059 & 0.6327 \\ 1.0000 & 0.0000 & 1.0000 \\ 0.9970 & 1.0000 & 1.0000 \\ 1.0000 & 0.9376 & 0.9562 \\ 1.0000 & 0.0000 & 1.0000 \\ 1.0000 & 0.5909 & 0.0909 \\ 1.0000 & 0.1358 & 0.3928 \end{bmatrix}$$

### 3.2.2 Determining city weights by the Entropy Weight Method

To obtain the weights of the three cities of Nanjing-Zhenjiang-Yangzhou objectively, this paper takes into account the regional gross domestic production, gross regional product index, year-end household population, local general public budget revenue and budget expenditure of Nanjing-Zhenjiang-Yangzhou from 2015-2019, and uses the entropy weight method to determine the weights of the three cities in each indicator. The data are obtained from the National Bureau of Statistics and the yearbook of Jiangsu Province in relevant years, and the detailed data are shown in Table V.

The indicators referred to by the entropy weight method here are the three cities of Nanjing-Zhenjiang-Yangzhou, and the normalized matrix of the three cities' data for each indicator in the above table is calculated:

$$\begin{aligned}
 Y_1 &= \begin{bmatrix} 1.0000 & 0.2849 & 0.0000 \\ 0.7193 & 0.5792 & 0.4032 \\ 0.4628 & 0.7974 & 0.5958 \\ 0.1815 & 1.0000 & 1.0000 \\ 0.0000 & 0.0000 & 0.0965 \end{bmatrix} & Y_2 &= \begin{bmatrix} 0.0000 & 0.0000 & 0.4138 \\ 0.1333 & 0.0571 & 0.0000 \\ 0.2000 & 0.3429 & 0.5862 \\ 0.2000 & 0.7429 & 0.9483 \\ 1.0000 & 1.0000 & 1.0000 \end{bmatrix} \\
 Y_3 &= \begin{bmatrix} 1.0000 & 0.9826 & 0.9910 \\ 0.7717 & 0.9900 & 0.9947 \\ 0.4833 & 0.9950 & 0.9954 \\ 0.1664 & 0.0000 & 0.0000 \\ 0.0000 & 1.0000 & 1.0000 \end{bmatrix} & Y_4 &= \begin{bmatrix} 1.0000 & 0.8760 & 1.0000 \\ 0.8036 & 0.0943 & 0.0630 \\ 0.4498 & 0.0000 & 0.0000 \\ 0.2189 & 1.0000 & 0.9133 \\ 0.0000 & 0.9358 & 0.9749 \end{bmatrix}
 \end{aligned}$$

$$Y_5 = \begin{bmatrix} 1.0000 & 1.0000 & 1.0000 \\ 0.7953 & 0.1170 & 0.0096 \\ 0.5037 & 0.0000 & 0.0000 \\ 0.2094 & 0.5490 & 0.6085 \\ 0.0000 & 0.4263 & 0.5546 \end{bmatrix}$$

The city weights are calculated by computing the information redundancy  $D_{j,k} = 1 - E_{j,k}$ . The weight of city j for indicator k is:

$$W_{j,k} = \frac{D_{j,k}}{\sum_{j=1}^m D_{j,k}} \tag{3}$$

where,  $E_{j,k} = -K \sum_{i=1}^t y_{ij} \ln y_{ij}$ ,  $m$  is the number of evaluated cities. Relevant statistics of Nanjing-Zhenjiang-Yangzhou Region

**Table V.** Relevant Data of Nanjing-Zhenjiang-Yangzhou Region

	Indicators	2019	2018	2017	2016	2015
Nanjing	Gross Domestic Product (billion yuan)	14030.15	12820.4	11715.1	10503.02	9720.77
	Gross regional product index (previous year = 100)	107.8	108	108.1	108.1	109.3
	Year-end household population (million)	709.82	696.94	680.67	662.79	653.4
	Local general public budget revenue (billion yuan)	1580.03	1470.02	1271.91	1142.6	1020.03
	Local general public budget expenditure (billion yuan)	1658.07	1532.72	1354.09	1173.84	1045.57
Yangzhou	Gross Domestic Product (billion yuan)	4539.12	5078.58	5478.74	5850.08	4016.84
	Gross regional product index (previous year = 100)	106.8	107	108	109.4	110.3
	Year-end household population (million)	457.14	458.83	459.98	232.47	461.12
	Local general public budget revenue (billion yuan)	328.79	224.72	212.17	345.3	336.75
	Local general public budget expenditure (billion yuan)	611.95	351.59	317.09	478.97	442.78
Zhenjiang	Gross Domestic Product (billion yuan)	3435.73	3714.57	3847.79	4127.32	3502.48
	Gross regional product index (previous year = 100)	106.2	103.8	107.2	109.3	109.6
	Year-end household population (million)	270.16	270.78	270.9	103.42	271.67
	Local general public budget revenue (billion yuan)	306.85	157.33	147.28	293.01	302.85
	Local general public budget expenditure (billion yuan)	466.25	204.93	202.4	362.94	348.73

The city weights of the indicators from 1 to  $t$  are summed and normalized to obtain the vector of city weights in the evaluation matrix.

$$W' = \{w_1, w_2, \dots, w_m\}^T = \frac{\sum_{k=1}^t W_{j,k}}{\sum_{j=1}^m \sum_{k=1}^t W_{j,k}} \tag{4}$$

Where  $w_j \in [0,1]$ .

The city data weights are calculated to obtain the weights  $W' = \{0.3564, 0.3157, 0.3280\}^T$  for the three cities of Nanjing-Zhenjiang-Yangzhou in the governance scheme.

### 3.2.3 Constructing a decision matrix

From the city weight matrix  $W'$  and the normalized

quantitative sample matrix  $\bar{X}$  the quantitative indicator decision vector  $A = \{a_1, a_2, \dots, a_i, \dots, a_n\}^T$  is obtained

$$A = X \times W_j' = \sum_{j=1}^m x_{ij} w_j \quad (5)$$

Where  $a_i \in [0,1], i = 1,2, \dots, n$ .

In order to make the decision matrix of qualitative indicators fall into the range of [0,1] which is consistent with the quantitative indicators, the evaluation scores of each expert for each indicator are transformed into [0,1] and the mean value  $b_i$  is taken as the decision vector  $B = \{b_1, b_2, \dots, b_i, \dots, b_s\}^T$  for qualitative indicators.

$$b_i = \frac{\sum_{r=1}^p y_{ir}}{p} \quad (6)$$

where  $y_{ir}$  is the value assigned to the  $i$ -th indicator by the  $r$ -th evaluator,  $p$  is the number of experts, and  $s$  is the number of qualitative evaluation indicators,  $i = 1,2, \dots, n$ .

So far, we can obtain the sample matrix for the evaluation of water pollution synergy management in Nanjing-Zhenjiang-Yangzhou metropolitan area  $D = \left(\frac{A}{B}\right) = \{0.4933, 0.4849, 0.6371, 0.7308, 0.5421, 0.9589, 0.9148, 0.5244, 1.0000, 1.0000, 0.6920, 0.6843, 0.9989, 0.9659, 0.6843, 0.3667, 0.3667, 0.7000, 0.5727, 0.5281\}$

### 3.3 Determination of indicator weights

In the multi-layer index system, different indicators have different contributions to the evaluation system and there are different degrees of correlation among the indicators, so it is necessary to assign weights to each indicator according to its contribution degree and correlation degree. The fuzzy hierarchical analysis method combines the advantages of hierarchical analysis and fuzzy comprehensive evaluation method, which can be used to measure the weight of qualitative and quantitative, definite and uncertain indicators, and to fuzzify the subjectivity of experts<sup>[11]</sup> and transform them into accurate decision-making information.

#### 3.3.1 Constructing the fuzzy complementary consistency matrix

A fuzzy complementary consistency matrix characterizing the relative importance of any two factors in the set  $I = \{I_1, I_2, \dots, I_n\}$  can be constructed

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nn} \end{bmatrix} \circ$$

Where  $r_{ij} + r_{ji} = 1, 0 \leq r_{ij} \leq 1 (i, j = 1,2, \dots, n)$ . A larger  $r_{ij}$  means that factor  $I_i$  is more important than factor  $I_j$ . In particular, when  $r_{ij} = 0.5$  means that both factors are equally important.

The literature<sup>[12]</sup> provides a method to construct a fuzzy complementary matrix starting from the traditional judgment matrix of hierarchical analysis. The fuzzy

consistent judgment matrix is constructed for the first level of judging index factors as follows.

$$R = \begin{bmatrix} 0.5000 & 0.7386 & 0.5880 & 0.5880 & 0.6505 & 0.3495 \\ 0.2614 & 0.5000 & 0.3495 & 0.3495 & 0.4120 & 0.1109 \\ 0.4120 & 0.6505 & 0.5000 & 0.5000 & 0.5625 & 0.2614 \\ 0.4120 & 0.6505 & 0.5000 & 0.5000 & 0.5625 & 0.2614 \\ 0.3495 & 0.5880 & 0.4375 & 0.4375 & 0.5000 & 0.1990 \\ 0.6505 & 0.8891 & 0.7386 & 0.7386 & 0.8010 & 0.5000 \end{bmatrix}$$

#### 3.3.2 Calculation of index weights

Based on the above definition of fuzzy complementary consistency matrix, the weights of each factor under a certain attribute can be determined by equation (7).

$$w_i(\beta) = \frac{\beta^{\frac{1}{n} \sum_{j=1}^n r_{ij}}}{\sum_{k=1}^n \beta^{\frac{1}{n} \sum_{j=1}^n r_{kj}}}, i = 1,2, \dots, n \quad (7)$$

Where  $\beta > 1$

Considering the resolution of program advantages and disadvantages, taking the base  $\beta = 100$ , the weight vector of the first-level indicators is obtained as  $w(100) = \{0.1935, 0.0645, 0.1290, 0.1290, 0.3871, 0.0968\}^T$ , and the corresponding fuzzy consistent judgment matrix of the second-level indicators is shown in Table VI, and the weights of indicators at all levels are assigned as shown in Table VII.

**Table VI.** Determination of weights of Second-level indicators

Second-level indicators	Fuzzy consistent judgment matrix
$I_{P1} = \{P11, P12, P13\}$	$R = \begin{bmatrix} 0.5000 & 0.4120 & 0.2614 \\ 0.5880 & 0.5000 & 0.3495 \\ 0.7386 & 0.6505 & 0.5000 \end{bmatrix}$
$I_{S1} = \{S11, S12\}$	$R = \begin{bmatrix} 0.5000 & 0.9225 \\ 0.0775 & 0.5000 \end{bmatrix}$
$I_{R1} = \{R11, R12, R13, R14\}$	$R = \begin{bmatrix} 0.5000 & 0.6505 & 0.8010 & 0.7386 \\ 0.3495 & 0.5000 & 0.6505 & 0.5880 \\ 0.1990 & 0.3495 & 0.5000 & 0.4375 \\ 0.2614 & 0.4120 & 0.5625 & 0.5000 \end{bmatrix}$
$I_{R2} = \{R21, R22, \dots, R2n\}$	$R = \begin{bmatrix} 0.5000 & 0.3495 & 0.5000 & 0.3495 & 0.588 \\ 0.6505 & 0.5000 & 0.6505 & 0.5000 & 0.738 \\ 0.5000 & 0.3495 & 0.5000 & 0.3495 & 0.588 \\ 0.6505 & 0.5000 & 0.6505 & 0.5000 & 0.738 \\ 0.4120 & 0.2614 & 0.4120 & 0.2614 & 0.500 \\ 0.5000 & 0.3495 & 0.5000 & 0.3495 & 0.588 \end{bmatrix}$
$I_{R3} = \{R31, R32, R33\}$	$R = \begin{bmatrix} 0.5000 & 0.8010 & 0.6505 \\ 0.1990 & 0.5000 & 0.3495 \\ 0.3495 & 0.6505 & 0.5000 \end{bmatrix}$
$I_{Q1} = \{Q11, Q12\}$	$R = \begin{bmatrix} 0.5000 & 0.2614 \\ 0.7386 & 0.5000 \end{bmatrix}$

**Table VII.** Weights of Second-level indicators

Weights of first-level indicators	Weights of second-level indicators	Weights in total
0.1935	$w(100) = \begin{pmatrix} 0.1818 \\ 0.2727 \\ 0.5455 \end{pmatrix}$	0.0352
		0.0528
		0.1056
0.0645	$w(100) = \begin{pmatrix} 0.875 \\ 0.125 \end{pmatrix}$	0.0565
		0.0081
0.1290	$w(100) = \begin{pmatrix} 0.48 \\ 0.24 \\ 0.12 \\ 0.16 \end{pmatrix}$	0.0619
		0.0310
		0.0155
		0.0206
0.1290	$w(100) = \begin{pmatrix} 0.1304 \\ 0.2609 \\ 0.1304 \\ 0.2609 \\ 0.0870 \\ 0.1304 \end{pmatrix}$	0.0168
		0.0337
		0.0168
		0.0337
		0.0112
		0.0168
0.3871	$w(100) = \begin{pmatrix} 0.5714 \\ 0.1429 \\ 0.2857 \end{pmatrix}$	0.2212
		0.0553
		0.1106
0.0968	$w(100) = \begin{pmatrix} 0.25 \\ 0.75 \end{pmatrix}$	0.0242
		0.0726

**3.4 Establishing a gray evaluation model with mixed centroid whitening weight function**

In order to avoid simple and rough evaluation, and to consider the problem of multiple crossovers of gray class whitening weight functions, and to ensure that the probability sum of each gray class of the same index is equal to 1, this paper adopts a hybrid centroid triangular whitening weight function gray clustering evaluation model to evaluate the collaborative governance scheme.

The sample vector construction method in this paper has a major feature that  $d_i \in [0,1]$  for all elements of the sample vector D. In this paper, this range of values is divided into four gray classes: unqualified, qualified, good, and excellent, which correspond to gray classes  $k = 1,2,3,4$  respectively, as shown in Table VIII.

**Table VIII.** Grey classes of indicators and the range

gray class $k$	1	2	3	4
range of values	[0, 0.3]	[0.3, 0.5]	[0.5, 0.7]	[0.7, 1]

According to  $\lambda_k = \frac{d_k + d_{k+1}}{2}$  determine the center

point of the gray class  $\lambda_1 = 0.2, \lambda_2 = 0.4, \lambda_3 = 0.6, \lambda_4 = 0.8$ , and also expand the first gray class and the last gray class to both sides to  $\lambda_0 = 0$  and  $\lambda_5 = 1$ . Construct the mixed center point whitening power function as follows, the function is shown in Figure I.

$$f^1(x) = \begin{cases} 0, & x \notin [0, 0.4] \\ 1, & x \in [0, 0.2] \\ \frac{0.4-x}{0.2}, & x \in [0.2, 0.4] \end{cases}$$

$$f^2(x) = \begin{cases} 0, & x \notin [0.2, 0.6] \\ \frac{x-0.2}{0.2}, & x \in [0.2, 0.4] \\ \frac{0.6-x}{0.2}, & x \in [0.4, 0.6] \end{cases}$$

$$f^3(x) = \begin{cases} 0, & x \notin [0.4, 0.8] \\ \frac{x-0.4}{0.2}, & x \in [0.4, 0.6] \\ \frac{0.8-x}{0.2}, & x \in [0.6, 0.8] \end{cases}$$

$$f^4(x) = \begin{cases} 0, & x \notin [0.6, 1] \\ \frac{x-0.6}{0.2}, & x \in [0.6, 0.8] \\ 1, & x \in [0.8, 1] \end{cases}$$

The affiliation degree  $f_i^k(d_i)$  of the scheme belonging to the gray class  $k(k = 1,2, \dots, q)$  can be calculated by using the hybrid centroid triangular whitening weight function and the sample values of each indicator. Based on the sample value  $d_{ij}$  of the primary indicator  $i$  secondary indicator  $j$ , let  $f^k(x)$  be the mixed centroid triangular whitening weight function of subclass  $k$ . Then, using the primary indicator weight  $w^*$  and the secondary indicator weight  $w$  to weight the sample value of each secondary indicator, we can calculate the comprehensive clustering coefficient of the scheme

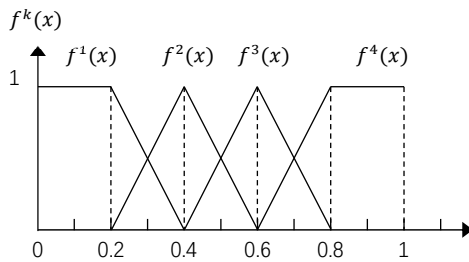
$$\sigma^k = f^k \left( \sum_{i=1}^n w_i^* \cdot \sum_{j=1}^m d_{ij} w_j \right) \tag{8}$$

The final results are shown in Table IX.

**Table IX.** Grey clustering coefficients of water pollution synergistic management scheme in Nanjing-Zhenjiang-Yangzhou metropolitan area

$k$	1	2	3	4
$\sigma^k$	0	0	0.9453	0.0545





**Figure 1** Whitening power function for the evaluation of water pollution synergistic management scheme in Nanjing-Zhenjiang-Yangzhou metropolitan area

The gray class to which the object belongs is determined by  $\sigma_i^k = \max_{1 \leq k \leq n} \{\sigma_i^k\}$ , then the gray class  $k$  corresponding to  $\sigma_i^k$  is the class to which the clustered object belongs.

$\max_{1 \leq k \leq 4} \{\sigma^k\} = \max_{1 \leq k \leq 4} \{0, 0, 0.9453, 0.0545\} = 0.9453 = \sigma^3$ . Therefore, the corresponding gray category of Nanjing-Zhenjiang-Yangzhou metropolitan area water pollution management program is the third category, and the comprehensive assessment level is good.

## 4 Conclusions

Located in the Yangtze River basin, the Nanjing-Zhenjiang-Yangzhou metropolitan area was embedded in the integrated development process of the Yangtze River Delta city cluster in 2014, in order to promote urban integration and achieve synergistic cooperation and integrated development among different cities. In this environment, the collaborative water pollution management in Nanjing-Zhenjiang-Yangzhou metropolitan area is also in a difficult situation, and it is urgent to solve the management problem and break the current water pollution dilemma. The conclusion at the end of the paper leads us to make policy recommendations in the following aspects.

### 4.1 Strengthen top-level construction and establish a coordinating body

It is impossible to establish a new regional governing body in the Nanjing-Zhenjiang-Yangzhou region. A more realistic approach is to form a long-term, comprehensive and mutual dialogue regional management group through consultation with a fixed number of representatives from each city, and to establish a communication mechanism for coordinated regional development. The regional management group coordinates their respective interests and resolves disputes in development according to the overall development situation, such as formulating long-term development plans, upgrading and optimizing industries, achieving environmental and ecological protection and sustainable development, so as to avoid duplicate construction, industrial convergence and low resource allocation, and to improve regional resource integration.

### 4.2 Application of modern information technology to achieve information sharing

At present, the water environment pollution problems in Ning, Zhen and Yang cannot be effectively managed, and the root of the problem is that the information cannot be shared in real time effectively. It refers to the use of the Internet and various intelligent sensor devices to form a network system that connects people, things and information to each other, thus realizing digitalization, visualization, intelligence and remote management and control, which truly realizes the collaborative governance of "Internet of everything".

### 4.3 Unification of laws and regulations

The legal regulations of the unified watershed, the basic principles of the establishment of cross-regional ecological compensation mechanism, compensation standards, multiple subjects and joint measures, so that the three cities of Ning, Zhen and Yang will take the construction of the Yangtze River Ecological Civilization Innovation Center as the starting point, better use of legal means to protect the ecology of the Yangtze River Ning, Zhen and Yang section, the Yangtze River protection requirements to the letter.

### 4.4 Establish a reasonable and effective evaluation mechanism

A scientific and reasonable evaluation mechanism can truly evaluate the current status of governance, expose the problems in the process of governance, and provide the right direction for further improvement of governance programs and optimization of governance processes.

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