Comprehensive benefit analysis of regional water resources based on multi-objective evaluation

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Abstract. The purpose of the water resources comprehensive benefits analysis is to maximize the comprehensive benefits on the aspects of social, economic and ecological environment. Aiming at the defects of the traditional analytic hierarchy process in the evaluation of water resources, it proposed a comprehensive benefit evaluation of social, economic and environmental benefits index from the perspective of water resources comprehensive benefit in the social system, economic system and environmental system; determined the index weight by the improved fuzzy analytic hierarchy process (AHP), calculated the relative index of water resources comprehensive benefit and analyzed the comprehensive benefit of water resources in Xiangshui County by the multi-objective evaluation model. Based on the water resources data in Xiangshui County, 20 main comprehensive benefit assessment factors of 5 districts belonged to Xiangshui County were evaluated. The results showed that the comprehensive benefit of Xiangshui County was 0.7317, meanwhile the social economy has a further development space in the current situation of water resources.

1. Introduction
The global water resources is currently experiencing a crises that is restricting society development in many countries. Due to the growing shortage of water resources, the comprehensive benefit evaluation of water resources has special significance. It is an important content and basic work to establish a scientific and reasonable evaluation index system, which is related to the correctness of the evaluation results. The regional water resources assessment is a comprehensive system which usually consists of various factors and many evaluation methods have been proposed for such system with multiple factors [1]. The commonly used subjective weighting methods, such as analytic hierarchy process (AHP) and Delphi method, mainly reflecting the relative importance of indicators. The objective weighting methods, including variation coefficient method, standard deviation method and entropy weight ideal point method, which always reflect the discriminating degree of index data [2-4]. There are no better or worse techniques, but some techniques may better suit to particular decision problems than others do [2]. AHP method, established by Saaty in 1997, is a useful tool dealing with imprecise,
uncertain or ambiguous data [5]. The method widely applied to decision problems in issues such as complexity of ecosystems and environmental [6].

Water resources exploited are not only restricted by water resources but also influenced by economy condition, social factors and ecological environment factors. Meanwhile, social, economic and environmental benefits are all affected by different specific indicators. The comprehensive benefit analysis of regional water resources aims to maximize the comprehensive benefit of water resources in the aspects of economy, society and ecology [7]. The evaluation result is instructive to optimal allocation and scientific management of water resources. In this paper, we analyzed and evaluated the comprehensive benefit of water resources in Xiangshui County from the aspects of influencing factors, index system and evaluation method. Criterion layer was developed to measure important aspects of the comprehensive water utilization benefits: social benefit, economic benefit and environmental benefit. The rational evaluation results by improved fuzzy AHP should be able to objectively reflect the comprehensive benefits of water resources. It can dynamically detect and diagnose on optimal operation of water resources, timely find out the problems in the process of water resources utilization, and provide a scientific basis for further improving the sustainable utilization of water resources.

2. Establish the index system based on multi-objective evaluation

2.1. Establish the fuzzy judgment matrix and pseudo optimal transfer matrix

A direct comparison matrix $F = (f_{ij})_{nm}$ is established by the importance of elements at each level:

$$f_{ij} = \begin{cases} 
2 & \text{i is more important than j} \\
1 & \text{i is as important as j} \\
0 & \text{j is more important than i}
\end{cases}$$  \hspace{1cm} (1)

The sum of row elements of the three scale compares matrix F can be defined as $r_i = \sum_{j=1}^{n} f_{ij}, i = 1, 2, \cdots, n$, based on two basic point comparative factors $r_{\max}$ and $r_{\min}$, the basic point comparison scale is obtained as $b_m$.

Through the transformation of Eq. (2), the direct comparison matrix $F$ is transformed into an indirect fuzzy judgment matrix $A = (a_{ij})_{nm}$:

$$a_{ij} = \begin{cases} 
\frac{r_i - r_j}{r_{\max} - r_{\min}}(b_m - 1) + 1 & r_i \geq r_j \\
\frac{r_j - r_i}{r_{\max} - r_{\min}}(b_m - 1) + 1 & r_i < r_j
\end{cases}$$  \hspace{1cm} (2)

The above indirect judgment matrix $A$ is not necessarily satisfy the consistency of thinking judgment, which need carry on consistency check of the judgment matrix. If the consistency test does not meet the requirement, the scale value of the element must be readjusted, which may exist the problems of big calculation and a certain blindness.

Therefore, the algorithm is improved in this step, by using the concept of pseudo optimal transfer matrix, the matrix $A$ is transformed and a judgment matrix $A'$ which satisfies the consistency requirement is obtained. The detailed process is first solving the antisymmetric matrices of $A$ expressed as $E = \ln A$, and then construct a matrix $A' = [10^{C_{ij}}]$. The $C_{ij}$ of a matrix is given by Eq. (3):
\[ c_{ij} = \frac{1}{n} \sum_{k=1}^{n} (e_{ik} - e_{jk}) \]  \hspace{1cm} (3)

Where the matrix \( A^* \) is the pseudo optimal transfer matrix of \( A \).

2.2. Calculate the weight

Based on the quasi-optimal transfer matrix \( A^* = (a_{ij})_{n \times n} \), the root method is used to calculate eigenvectors corresponding to the largest eigenvalue. And the weights could be calculated as follows.

Step 1: The elements of \( A \) are multiplied by rows. \( u_j = \prod_{j=1}^{n} A^* \)

Step 2: Extraction of a root. \( u_j = \sqrt{n} u_{ij} \)

Step 3: Regularization of the root vectors. \( \omega_j = \frac{u_i}{\sum_{j=1}^{n} u_i} \)

Step 4: Calculate the accuracy of power method. The weight vector \( \omega^{(0)} \) is the initial value \( V_0 \) of power method. And the next step is to find the higher precision weight vector \( \omega^{(k)} \).

2.3. Establish the regional water resources comprehensive benefit evaluation model

There are various types of indexes reflecting the comprehensive benefits of water resources, which cover all fields of society, economy and ecology. The indexes of comprehensive benefit of water resources not only have different dimensions, but also have great difference in the numerical magnitude. In order to eliminate the influence of these differences and avoid the occurrence of irrational phenomena, the indicators should be treated with method for non-dimensional. The non-dimensional formula of indexes can be expressed as:

\[
M_j = \max \{ x_{ij} \} \quad m_j = \min \{ x_{ij} \} \\
X_{ij} = (x_{ij} - m_j)/(M_j - m_j) \]  \hspace{1cm} (4)

Where \( X_{ij} \) and \( x_{ij} \) denotes the standard value and the original value of the j sub-index of i index in the previous hierarchy, respectively. \( m_j \) and \( M_j \) represents the lower limit and the upper limit of the range in which the original value \( x_{ij} \) is located.

According to the processed indexes, the comprehensive evaluation model of water resources is established:

\[ W_i = \sum_{j=1}^{n} w_j X_{ij} \]  \hspace{1cm} (5)

Where \( W_i \) is the weight of the i index in the previous hierarchy, \( w_j \) is the weight vector of the j index among the second indicators.
3. Case study

3.1. Study area
The Xiangshui County, located in the northeast coast of Jiangsu Province, is situated in the junction of three cities named Lianyungang, Huaian and Yancheng. There is a Zhongshan River in the south of the county, with a total length of 63km and the flow rate of 150-200m³/s. The Tongyu Grand Canal with domestic length of 20km, located in the west of the county, is as wide as 100 meters. The water resources of Xiangshui County mainly include transit water and groundwater. The total annual water consumption in Xiangshui County is about 500 million m³, and the water supply for agriculture, producing and living largely rely on the upper reaches of the Yellow River and Inter-Basin water transfer system. Because of the upstream interception, the water supply is seriously insufficient in the middle and lower reaches. According to the characteristics of the water network, natural geographical conditions and the development and utilization of water resources, the Xiangshui County could be divided into five subregion: the West region of Yunxiang River, the North region of Nanchao River, the South region of Nanchao River, the Bund District and the Saltern District.

3.2. Constructing evaluation index system of comprehensive benefits of water resources
A region uses various indicators to evaluate whether the comprehensive benefit of water resources meets the financing requirement by the local social and economic development. According to the actual characteristics of water resources of each region in Xiangshui County, Jiangsu Province, the hierarchical structure of water resources comprehensive benefit (A) based on regional economic benefit (C1), social benefit (C2) and environmental benefit (C3) was constructed. The evaluation index values were shown in Table 1.
Table 1. The evaluation index values of comprehensive benefits in Xiangshui County

| Goal                  | Criteria          | Evaluation items                                                                 |
|-----------------------|-------------------|----------------------------------------------------------------------------------|
| Economic              | Benefit(C1)       | P11 the ratio of agricultural output value to total output                        |
|                       |                   | P12 the ratio of agricultural water consumption                                   |
|                       |                   | P13 the ratio of grain crops                                                      |
|                       |                   | P14 single cubic water output of irrigation quota                                 |
|                       |                   | P15 water consumption of ten-thousand-yuan production value of industry           |
|                       |                   | P16 GDP output value of single cubic water                                        |
|                       |                   | P17 industrial output value of single cubic water                                 |
|                       |                   | P18 daily water consumption per capita                                           |
|                       |                   | P19 comprehensive water consumption per capita                                   |
| Comprehensive Social  | Benefit(C2)       | P21 social total production value                                                 |
| benefit               |                   | P22 GDP per capita                                                                |
|                       |                   | P23 farmers' per capita income                                                    |
|                       |                   | P24 water-saving irrigation area                                                  |
|                       |                   | P25 national income of single cubic water                                         |
|                       |                   | P26 population density                                                            |
|                       |                   | P27 regional GDP growth rate                                                      |
| Environmental         | Benefit(C3)       | P31 forest cover rate                                                              |
| benefit               |                   | P32 eco-environmental water demand                                                |
|                       |                   | P33 wastewater discharge of ten thousand yuan production value of industry        |
|                       |                   | P34 wastewater discharge of ten thousand yuan GDP                                  |

3.3. Calculation of the comprehensive benefit of water resources

Using the improved fuzzy AHP method to calculate the comprehensive benefit of water resources in Xiangshui County. According to the Eq. (3), dimensionless values of each index was treated. The relative value of each index was displayed in Table 2.
### Table 2. Relative index values of comprehensive benefit of water resources

| Evaluation items | XC  | WYR | NNR | SNR | BD  | SD  |
|------------------|-----|-----|-----|-----|-----|-----|
| P11              | 0.613 | 0.5276 | 0.5191 | 1.3584 | 0.6823 | 0 |
| P12              | 0.9239 | 0.9112 | 0.8419 | 1.9895 | 0.9884 | 0 |
| P13              | 0.2321 | 0.8323 | 0.9829 | 2.8806 | 1.2511 | 0 |
| P14              | 0.187 | 0.1609 | 0.2244 | 1.1634 | 0.1727 | 0 |
| P15              | 0   | 0.0623 | 0.03 | 0.2199 | 0.382 | 1 |
| P16              | 1   | 0.9405 | 0.9714 | 1.7968 | 0.6368 | 0 |
| P17              | 0.2321 | 0.4502 | 0.1858 | 0.0359 | 0 |
| P18              | 0.5294 | 0.6759 | 0.7678 | 0.6694 | 0 | 1 |
| P19              | 0.5294 | 0.6759 | 0.7678 | 0.6694 | 0 | 1 |
| P21              | 1   | 0.2425 | 1.5811 | 2 | 0.3304 | 0 |
| P22              | 0.8806 | 0.9248 | 1 | 1.5851 | 0.7794 | 0 |
| P23              | 0.8645 | 1 | 0.8688 | 1.7408 | 0.8475 | 0 |
| P24              | 1   | 0.2612 | 0.3204 | 0.3442 | 0.0741 | 0 |
| P25              | 0.4833 | 0.4836 | 1 | 0.1476 | 0.2605 | 0.9226 |
| P26              | 0.5496 | 0.8483 | 1 | 0.9364 | 0.7218 | 0 |
| P27              | 1   | 0.2501 | 0.261 | 0.2461 | 0.2381 | 0 |
| P31              | 0.3814 | 0.6385 | 0.4765 | 0.5989 | 1 | 0 |
| P32              | 1   | 0.113 | 0.0325 | 0.1196 | 0.1207 | 0.1285 |
| P33              | 0   | 0.2214 | 0.339 | 0.2859 | 0.053 | 0 |
| P34              | 0   | 0.2214 | 0.339 | 0.2859 | 0.053 | 0 |

(Note: XC represents the whole Xiangshui County, WYR represents the West region of Yunxiang River, NNR represents the North region of Nanxiao River, SNR represents the South region of Nanchao River, BD represents the Bund District and SD represents the Saltern District.)

In the hierarchical structure of water resources comprehensive benefit index, we compared and judged the relative importance of the next layer index that affect the upper layer. Using the three-scaling method, these judgments were represented by numerical values, and a direct comparison matrix of the next layer was established.

Evaluation of economic benefit

\[
D_1 = \begin{bmatrix}
1 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 2 & 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 2 & 2 & 2 & 1 & 0 & 0 & 0 & 0 & 0 \\
2 & 2 & 2 & 2 & 2 & 1 & 2 & 0 & 0 & 0 \\
2 & 2 & 2 & 2 & 2 & 2 & 0 & 1 & 0 & 0 \\
2 & 2 & 2 & 2 & 2 & 2 & 2 & 1 & 0 & 0 \\
2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 1 & 0 \\
\end{bmatrix}
\]

Figure 1. Judgment matrix of economic benefit D1:

Calculates the maximum and minimum values of the sum of the row elements in the direct comparison matrix \( D_1 \), the value was obtained by \( r_{\text{max}} = 17 \), \( r_{\text{min}} = 1 \). Comparison scale of the base point was showed as \( b_m = 9 \), then the indirect judgment matrix \( A_1 \) was obtained by Eq. (2). The antisymmetric matrix \( E_1 \) was given by the formula of \( E = 10^{A_1} \). For the quasi-optimal transfer matrix \( A^* \), we got its value based on the following equation: \( a^*_v = 10^{C_v} = 10^\frac{1}{\gamma} \sum_{i,j} (c_{ij} - p_{ij}) \).
Figure 2. Judgment matrix of economic benefit

Weight vector $\omega_1$ was got by calculating eigenvectors of corresponding characteristic roots that were maximum.

$$\omega_1 = (0.0295, 0.0464, 0.0359, 0.0484, 0.0797, 0.1491, 0.1029, 0.2121, 0.2960)$$

Evaluation of social benefit, environmental benefit and comprehensive benefit

According to the method of economic benefit evaluation in step (1), weight vectors of social benefit indicators ($P_{21}-P_{27}$) and environmental benefit indicators ($P_{31}-P_{34}$) were determined as:

$$\omega_2 = (0.1041, 0.1596, 0.0308, 0.0678, 0.2412, 0.0449, 0.3516)$$

$$\omega_3 = (0.0954, 0.4668, 0.1602, 0.2776)$$

$$\omega = (0.5586, 0.1692, 0.2722)$$

(3) Based on the dimensionless indexes of water resources comprehensive benefit, and combined with the evaluation index weights, we analyzed the relative index values using multi-objective evaluation model of water resources comprehensive benefit (Eq. (4)) in Xiangshui County. The relative index values of each index layer in the whole and different regions of Xiangshui County were shown in Table 3.

Table 3. The relative index value in the whole and different regions of Xiangshui County

| Criteria | XC   | WYR  | NNR  | SNR  | BD   | SD   |
|----------|------|------|------|------|------|------|
| C1       | 0.5993 | 0.6111 | 0.6842 | 0.9368 | 0.2483 | 0.5878 |
| C2       | 0.8319 | 0.464 | 0.7505 | 0.7023 | 0.3689 | 0.2225 |
| C3       | 0.941 | 0.2106 | 0.209 | 0.2381 | 0.1749 | 0.0459 |
| A        | 0.7317 | 0.4772 | 0.5661 | 0.7069 | 0.2488 | 0.06  |

3.4. Calculation results and analysis

(1) The economic benefit index of water resources could directly reflect the economic benefit level of water resources utilization, and the result may be helpful to reveal the problems and contradictions in the management of water resources. It is of great significance for the rational allocation, planning, management and utilization of water resources and play an important role in bringing about the greatest economic benefit of water resources. From the evaluation results of economic benefit subsystem, the economic membership degree in the whole county is about 0.5993, the membership degree of each district in criteria layer is between 0.2483-0.9368. The South region of Nanchao River is the highest that up to 0.9368, which has reached a higher level of profitability compared with other areas. According to the evaluation results of social benefit subsystem, the social membership degree in the whole county is near 0.8319, the membership degree of each district in social criteria layer is between 0.2225 and 0.7505. It is worth mentioning that the North region of Nanchao River is the highest that up to 0.7523. In terms of the results of environmental benefit, the membership degree of each region in environmental criteria layer is between 0.0459-0.2381. Among them, the South region of Nanchao River is the highest that up to 0.2381. The results show that benefit range in a diminishing sequence of environmental from the South region of Nanchao River, the West region of Yunxiang...
River, the North region of Nanchao River, the Bund District to the Saltern District. From the evaluation results of comprehensive benefit, the comprehensive membership degree in the whole county is 0.7317, the membership degree of each region in comprehensive criteria layer is between 0.0600-0.7069.

(2) The water resources development and utilization degree of 5 regions in Xiangshui County were divided into 3 grades: I (0.6-0.9), II (0.3-0.6) and III (0-0.3). The comprehensive benefit of water resources in the South region of Nanchao River was grade I, which showed that the level of water resources development was high, it also meant that the potential for further development and utilization was small, thus a shortage of regional water resources may emerge in the future. For the Saltern District and the Bund District in Xiangshui County, the comprehensive benefit degree was relatively low, which indicated that comprehensive benefit belonged to grade III, promising huge potentials for water resources utilization and optimistic water supply situation in social economic development. However, in the process of economic construction, the water environment has deteriorated rapidly. We should strengthen the protection of water environment, and regional water resources development will remain a heated topic of debate for some time to come. For the West region of Yunxiang River and the North region of Nanchao River, the comprehensive benefit degree of water resources belonged to the II level. The development of water resources reached a decent size and possessed great development potential. Taking into account of development and utilization process in the future, we should pay more attention to pollution control and water conservancy projects construction.

The comprehensive benefit of Xiangshui County is 0.7317, although its comprehensive benefit of water resources are relatively low when compared with cities in the southern of Jiangsu Province. Anyhow, social economy has a further development in the present situation of water resources.

4. Conclusion
In view of the defects of the traditional analytic hierarchy process, such as large amount of calculation, low precision and one-sided results. In this paper, we adopted the improved fuzzy analytic hierarchy process to analyse the situation of water resources in Xiangshui County. The improved fuzzy AHP was simple and practical, it not only improved the speed of convergence but also ensured the accuracy. It’s really a good way to solve the rational allocation of water resources. According to the actual characteristics of Xiangshui County, a hierarchical structure of comprehensive benefit of water resources based on regional economic, social and environmental benefit was established. The combination weights of each index to the total target were analyzed and calculated, and the results were in good agreement with the actual situation in this region, denoting that the methods were very practical.

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