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Comprehensive evaluation of water resources carrying capacity in ecological irrigation districts based on fuzzy set pair analysis

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ABSTRACT

An ecological irrigation district is a compound ecosystem integrating production, life, and ecology. Based on the connotation of water resources carrying capacity (WRCC) in ecological irrigation districts, this paper comprehensively considers various factors affecting WRCC in ecological irrigation districts, establishes an evaluation index system of WRCC in ecological irrigation districts, and uses fuzzy set pair analysis theory to evaluate the WRCC in Dagong Yellow River Diversion Irrigation District from 2013 to 2017. The evaluation results show that the WRCC in the Dagong Yellow River Diversion Irrigation District was relatively weak from 2013 to 2014. In 2015, the Irrigation District gradually got rid of the water resources overload until 2017 when the WRCC of a large area in the irrigation district reached the carrying capacity. The evaluation results can provide a scientific basis for optimal allocation of water resources in the Dagong Yellow River Diversion Irrigation District.

Keywords: Ecological irrigation district; Water resources carrying capacity (WRCC); Fuzzy set pair analysis theory; Analytic hierarchy process (AHP)

1. Introduction

Ecological civilization is the foundation and guarantee of material civilization, spiritual civilization, political civilization, and social civilization construction. An ecological irrigation district is a compound ecosystem composed of social economy, water resources, and ecological environment, on the basis of a certain natural ecosystem and according to the needs of people's own development, which was proposed to point out the direction for the development of irrigation districts in China in the future, and many experts and scholars have researched its connotation [1–4], characteristics [5], and construction [6,7] in its ecological civilization construction. In order to strengthen and control the life process of agricultural organisms, obtain products that meet the needs of the society, and create a good production and living environment in the agricultural production activities of the whole irrigation districts, people can adjust the material transformation between man and nature by using a biological function and natural force and human subjective initiative and realize the sustainable development of irrigation districts by coordinating the relationship between organism and environment through labor [1].

Over the past 40 y of reform and opening up, along with the rapid development of rural economy in China, rural ecological environment problems have become increasingly prominent. As an important part of rural economic development and ecological construction, irrigation districts have been extensively studied in terms of water resources carrying capacity (WRCC), efficient allocation of water resources and water security evaluation. Besides, because water resources are important natural resources for production and life in

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irrigation districts, in order to better improve the problems of water resources such as water shortage, water environmental pollution, and groundwater funnel in the irrigation district of the Yellow River diversion in Henan Province, realize the rational development, utilization and protection of water and soil resources, coordinate the development of ecological environment and social economy, and promote the construction of ecological civilization and beautiful countryside, it is of great theoretical and practical significance to carry out the research on WRCC in the ecological irrigation districts [6].

2. Evaluation methodology of water resources carrying capacity in the ecological irrigation districts

With the passage of time and the impact of human activities on the environment, the WRCC in the ecological irrigation districts is the ability of water resources to support the sustainable development of social and economic system under the conditions of rational allocation and efficient utilization of water resources, taking sustainable development as the principle, promoting the virtuous cycle of an ecological environment as the premise, integrating economic and social development with modern technology [8,9]. The ecological irrigation districts integrate the agricultural ecosystem, ditch and lake ecosystem, forest and grass ecosystem, which need to be analyzed in carrying capacity calculation. The evaluation of WRCC in the ecological irrigation districts is actually a decision-making process combining the certainty of evaluation criteria with the uncertainty of weights of evaluation factors. In this paper, the fuzzy set pair analysis (SPA) and evaluation model was used to deal with the uncertainty and certainty in the water circulation system of irrigation districts.

2.1. Fuzzy set pair analysis and evaluation theory

Zhao Keqin, a Chinese scholar, put forward the SPA at the 1989 National Conference on Systems Theory and Regional Planning based on the viewpoint of the unity of opposites and universal connection in philosophy, with the core idea of constructing set pairs of two related sets in an uncertain system, and analyzing their identity, difference and opposition according to the characteristics, and then establishing the identical discrepancy contrary of them. At present, SPA has been widely used in many fields, such as mathematics, physics, information science, management science, economics, agricultural water conservancy science, ecology, resources and environmental science, education and so on, and a lot of research results have been obtained [10–12].

In order to fully consider the fuzziness of grade standard boundary and the different influence of each evaluation index, the improved fuzzy set pair analysis assessment method (FSPAAM) is proposed [13–15]. Compared with general SPA, FSPAAM considers the fuzziness of grade boundary and calculates the weight of index, which makes the calculation result more accurate and objective. From the point of view of systematicness and representativeness, the evaluation index system of hydrological and water resources system was selected and the grade evaluation criteria were determined. The specific evaluation process is as follows:

- Establish the evaluation index system. The factors affecting the development of irrigation districts were analyzed, and the evaluation index system x_i ($i = 1, 2, 3,\ldots, m$; where m is the number of evaluation indexes) of WRCC in the ecological irrigation districts was established.
- Determine the evaluation grade criteria. There is a standard method, reference method and expert judgment method to determine the evaluation grade criteria [16–20]. According to the actual situation of the study area, the evaluation grade criterion S_k (k = 1, 2, 3,…, k_1; where k is the number of evaluation grade) of WRCC in the ecological irrigation districts was determined by comprehensive consideration.
- Construct set pairs to calculate connection degree. The formula for calculating the degree of fuzzy connection is as follows:
  - The inverse index (the smaller the better), when $K > 2$, the K-element connection degree of set pairs is:

$$\mu_{A_i-B_1}=\begin{cases} 1+0I_1+0I_2+\cdots+0I_{k-2}+0J & x_i\le s_1\\ \dfrac{s_1+s_2-2x_i}{s_2-s_1}+\dfrac{2x_i-2s_1}{s_2-s_1}I_1+0I_2+\cdots+0I_{k-2}+0J & s_1<x_i\le\dfrac{s_1+s_2}{2}\\ 0+\dfrac{s_2+s_3-2x_i}{s_3-s_1}I_1+\dfrac{2x_i-s_1-s_2}{s_3-s_1}I_2+\cdots+0I_{k-2}+0J & \dfrac{s_1+s_2}{2}<x_i\le\dfrac{s_2+s_3}{2}\\ \cdots\cdots & \\ 0+0I_1+\cdots+\dfrac{2s_{k-1}-2x_i}{s_{k-1}-s_{k-2}}I_{k-2}+\dfrac{2x_i-s_{k-2}-s_{k-1}}{s_{k-1}-s_{k-2}}J & \dfrac{s_{k-2}+s_{k-1}}{2}<x_i\le s_{k-1}\\ 0+0I_1+0I_2+\cdots+0I_{k-2}+1J & s_{k-1}<x_i \end{cases} \quad (1)$$

where $s_1 \le s_2 \le \ldots \le s_{k-1}$.

- The positive index (the bigger the better), when $K > 2$, the K-element connection degree of set pairs is:

$$\mu_{A_i-B_1} = \begin{cases} 1+0I_1+0I_2+\cdots+0I_{k-2}+0J & x_i \ge s_1 \\ \dfrac{2x_i-s_1-s_2}{s_1-s_2}+\dfrac{2s_1-2x_i}{s_1-s_2}I_1+0I_2+\cdots+0I_{k-2}+0J & \dfrac{s_1+s_2}{2} \le x_i < s_1 \\ 0+\dfrac{2x_i-s_2-s_3}{s_1-s_3}I_1+\dfrac{s_1+s_2-2x_i}{s_1-s_3}I_2+\cdots+0I_{k-2}+0J & \dfrac{s_2+s_3}{2} \le x_i < \dfrac{s_1+s_2}{2} \\ \cdots\cdots & \\ 0+0I_1+\cdots+\dfrac{2x_i-2s_{k-1}}{s_{k-2}-s_{k-1}}I_{k-2}+\dfrac{s_{k-2}+s_{k-1}-2x_i}{s_{k-2}-s_{k-1}}J & s_{k-1} \le x_i < \dfrac{s_{k-2}+s_{k-1}}{2} \\ 0+0I_1+0I_2+\cdots+0I_{k-2}+1J & x_i < s_{k-1} \end{cases} \quad (2)$$

where $s_1 \ge s_2 \ge \ldots \ge s_{k-1}$.

- The calculation of index connection degree of evaluation sample set:

$$\mu_{A-B} = \sum_{i=1}^{m} \omega_i \mu_{A_i-B_1} = \sum_{i=1}^{m} \omega_i a_i + \sum_{i=1}^{m} \omega_i b_{i,1} I_1 + \sum_{i=1}^{m} \omega_i b_{i,2} I_2 + \cdots + \sum_{i=1}^{m} \omega_i b_{i,k-2} I_{k-2} + \sum_{i=1}^{m} \omega_i c_i J \quad (3)$$

where ω_i = the weight of i; a_i = the identical degree between x_i and s_k, the k-th grade criterion of the index; $b_{i,1}$ = the difference between index x_i and s_k, the k-th grade criterion of the index by one grade; $b_{i,2}$ = the difference between index x_i and s_k, the k-th grade criterion of the index by two grades; $b_{i,k-2}$ = the difference between index x_i and s_k, the k-th grade criterion of the index by k–2 grades; c_i = the contrary degree between index x_i and s_k, the k-th grade criterion of the index by k–1 grades.

Let $f_1 = \sum_{i=1}^{m} \omega_i a_i,\ f_2 = \sum_{i=1}^{m} \omega_i b_{i,1} \cdots,\ f_{k-1} = \sum_{i=1}^{m} \omega_i b_{i,k-2},\ f_k = \sum_{i=1}^{m} \omega_i c_i$, then Eq. (3) can be changed to

$$\mu_{A-B} = f_1 + f_2 I_1 + \cdots + f_{k-1} I_{k-2} + f_k J \quad (4)$$

Where, f_1 is the possibility that the evaluation sample is subordinate to the grade 1 criterion, and f_k is the possibility that the evaluation sample is subordinate to the grade k criterion.

- Comprehensive evaluation of WRCC. In order to avoid the subjective influence of the uncertain component coefficients ($I_1, I_2, \ldots, I_{k-2}$) in the determination of connection degree differences, the confidence criterion was used to judge the grade of the evaluation sample.

$$h_k = \left(f_1 + f_2 + \cdots + f_k\right) > \lambda,\ k = 1,2,\cdots,k \quad (5)$$

where λ = confidence coefficient, which should not be too large or too small, generally recommended to be between [0.50 and 0.70].

2.2. Establishment of comprehensive evaluation index system for ecological irrigation districts

The optimization of agricultural production structure, the benign operation of an ecosystem, the good quality of human settlements environment and the advanced social productivity in the ecological irrigation districts make them a complex ecosystem that can promote the sustainable and stable development of social economy and create beyond the natural productivity [7].

When constructing the comprehensive index system of ecological irrigation districts, in order to make the selected indexes scientific and standardized, the corresponding measurement criteria and evaluation methods should be combined, following the principles of systematicness, dynamism, typicality, and comprehensiveness [21]. On the whole, each evaluation index set should be classified and sorted, and a comprehensive evaluation index system conforming to the ecological irrigation districts is constructed, which will provide a scientific basis for revealing and coordinating the relationship between irrigation districts and population, society and economic environment [4,22–26].

In this paper, nine indexes are selected from three subsystems of social economy, water resources, and ecological environment. The indexes and their meanings are shown in Table 1.

2.3. Determination of weight of comprehensive evaluation index

According to the different sources of the original data, the method of weight calculation can be divided into subjective, objective, and combination weighting methods.

Table 1
Comprehensive evaluation index system of ecological irrigation districts

Objective	System	Evaluation indexes	Meaning
WRCC in the ecological irrigation districts	Socio-economic system	Average urbanization rate, X_1	The current level of social development
		Per capita GDP, X_2	The level of regional (irrigation districts) overall economic situation
	Water resources system	Effective irrigation area rate, X_3	Development of irrigation districts
		Effective coefficient of irrigative water utilization, X_4	Water use efficiency of irrigation water in irrigation districts
		Availability of water resources per capita, X_5	Degree of available water resources
		Utilization rate of water resources development, X_6	Availability of water resources
		Ratio of water deficiency, X_7	Difference between water demand and available water supply
	Ecosystem	Overdraft rate of shallow groundwater, X_8	Impact of water resources development and utilization on ecological environment
		Water use rate of ecological environment, X_9	Demand of ecosystems for water resources

The commonly used subjective weighting methods include the binomial coefficient method, analytic hierarchy process (AHP) [26], expert survey method, and the data used are mostly obtained by experts according to certain standards and combined with the actual situation. Commonly used objective weighting methods are principal component analysis method [27], entropy method [28], deviation, and mean square deviation method. When an objective weighting method is selected, the entropy method therein is used more. The data used in this method is the decision matrix, and the determined attribute weight can reflect the discrete degree of an attribute value.

In this paper, AHP was used to process and calculate data with MATLAB programming. AHP, as a common method to determine the weights of evaluation indexes, which has a clear concept, flexible and practical method, and simple calculation, was proposed by T.L. Saaty, an operational research scientist. Combining with the programming of MATLAB [29], the precision and accuracy of calculation results are better. The main process of determining index weight is as follows:

- Judgment matrix: The hierarchical structure of the evaluation index is constructed. According to expert experience and relevant statistical data, the importance of the evaluation index is evaluated by 1–9 scale method. The judgment matrix needs the following properties: (1) $a_{ij} > 0$; (2) $a_{ij} = 1/a_{ji}$; (3) $a_{ii} = 1$;
- Determination of weight: According to the judgment matrix, the eigenvalues and corresponding eigenvectors can be obtained, and the weights of each evaluation index can be obtained by normalization and standardization [30–34].
- Consistency checking: In order to test the consistency of the importance of each element in the judgment matrix, it is necessary to test the consistency of the matrix. Consistency checking is achieved by the consistency ratio CR = CI/RI. Among them, RI represents the average random consistency index, and the RI values corresponding to the judgment matrices of order 1–11 are shown in Table 2.

CI denotes the definition of compatibility index, which needs to be solved by combining the maximum eigenvalue λ_{max} of the judgment matrix. The calculation formulas are shown in Eqs. (6) and (7).

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \tag{6}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{7}$$

If CR < 0.1 or $\lambda_{max} = n$, it shows that the judgment matrix has a good consistency. Otherwise, it needs to be

Table 2
Values of RI

Order n	RI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.50

re-evaluated and the assignment of the judgment matrix is adjusted until the judgment matrix meets the requirements. In the above solving process, the Eigen function provided by the optimization toolbox of MATLAB was used to solve the mathematical model.

3. Examples

3.1. Grading criteria for evaluation indexes

In this paper, the WRCC in Dagong Irrigation District located in the north of Henan Province was evaluated, with the evaluation index data from Henan Water Resources Bulletin, Henan Statistical Yearbook of Water Resources, the 13th 5 y Plan data, and related investigation reports. The evaluation indexes were divided into four grades, including grade 1 for load, grade 2 for critical load, grade 3 for overload, and grade 4 for severe overload. The grading criteria of the evaluation index are detailed in Table 3.

3.2. Evaluation results

Let the evaluation index value of WRCC in Dagong Yellow River Diversion Irrigation District be set A and the grade 1 criterion of 9 indexes be set B, and take the WRCC in the Irrigation District in 2015 as an example, and use Eq. (4) to calculate the connection degree of each regional set to $H(A,B)$. The results are shown in the values of f_1, f_2, f_3, and f_4 in Table 4.

According to the confidence criterion, the grade of the sample was judged, that is, the h_k value was calculated by Eq. (5), and $\lambda = 0.55$. Then the WRCC of Neihuang County in 2015 was $h_1 = 0.248 < 0.55$, $h_2 = 0.310 < 0.55$, $h_3 = 0.570 < 0.55$, and $h_4 = 1 > 0.55$. The evaluation result shows that the WRCC of Neihuang County in 2015 was overload according to the confidence criterion. Similarly, the WRCC of all regions in the Dagong Irrigation District can be judged. The evaluation results are detailed in Table 4.

Based on the above methods, the comprehensive evaluation results of WRCC in the Dagong Yellow River Irrigation District in the recent 5 y can be obtained, as shown in Fig. 1. Among them, the overall WRCC in Dagong Yellow River Diversion Irrigation District in 2013 was seriously overloaded, which indicates that the water resources development there had far exceeded the available water resources during this period, and the sustainability of water resources was poor, and the carrying capacity was very weak. After the most stringent water resources management system was implemented in Henan Province, the WRCC of Changyuan and Fengqiu in the irrigation district was improved in 2014. By 2015, the irrigation district as a whole got rid of the predicament of serious overload. In 2017, except for Neihuang and Xunxian, the WRCC in the irrigation district was improved, and the situation of water resources was relatively stable. However, Neihuang and Xunxian are still in the overload area of water resources. The reason may be that in order to meet the needs of social and economic development, the expansion of groundwater funnel has not been effectively curbed by over-exploitation of groundwater for many years. In addition, the two counties are in the downstream of Dagong Irrigation District, and the upstream water supply index can't meet the downstream water demand, resulting in the local WRCC can't be significantly increased. According to the construction standard of ecological irrigation districts, the management department should further improve the water resources dispatch and allocation in Dagong Yellow River Diversion Irrigation District to ensure domestic and industrial water use and realize water supplement in flood season and water irrigation in non-flood season. As a result, the evaluation results in this paper are in accordance with the present situation of WRCC in irrigation districts.

4. Conclusions

Dagong Yellow River Diversion Irrigation District, as an important and core area for grain production in Henan Province, has water quality and water shortage problems. In this paper, according to the evaluation criteria of WRCC in the ecological irrigation districts, the WRCC in the Irrigation District was comprehensively evaluated by using the theory of fuzzy SPA. The evaluation results show that the WRCC in the Irrigation District from 2015 to 2017 had been greatly improved compared with the past. However, in order to meet the standard of ecological irrigation districts,

Table 3
Grading criteria for evaluation indexes

Indexes	Grading				Index weight
	Grade 1	Grade 2	Grade 3	Grade 4	
Average urbanization rate, X_1	<35	35–40	40–55	>55	0.0276
Per capita GDP, X_2	50,000	30,000–50,000	10,000–30,000	10,000	0.0828
Effective irrigation area rate, X_3	60	40–60	20–40	20	0.1862
Effective coefficient of irrigative water utilization, X_4	0.65	0.60–0.65	0.55–0.60	0.55	0.1655
Availability of water resources per capita, X_5	>500	400–500	300–400	<300	0.0414
Utilization rate of water resources development, X_6	<40	40–60	60–70	>70	0.1655
Ratio of water deficiency, X_7	<10	10–20	20–30	>30	0.0276
Overdraft rate of shallow groundwater, X_8	<10	10–17.5	17.5–25	>25	0.0552
Water use rate of ecological environment, X_9	>5	3–5	1–3	<1	0.2482

Table 4
Evaluation results of WRCC in Dagong Irrigation District (2015)

Regions	f_1	f_2	f_3	f_4	h_1	h_2	h_3	h_4	Grading
Neihuang	0.248	0.062	0.260	0.430	0.248	0.310	0.570		Overload
Xunxian	0.085	0.419	0.146	0.350	0.085	0.504	0.650		Overload
Huaxian	0.462	0.166	0.073	0.299	0.462	0.628			Critical load
Changyuan	0.358	0.208	0.141	0.293	0.358	0.566			Critical load
Fengqiu	0.327	0.267	0.185	0.220	0.327	0.594			Critical load

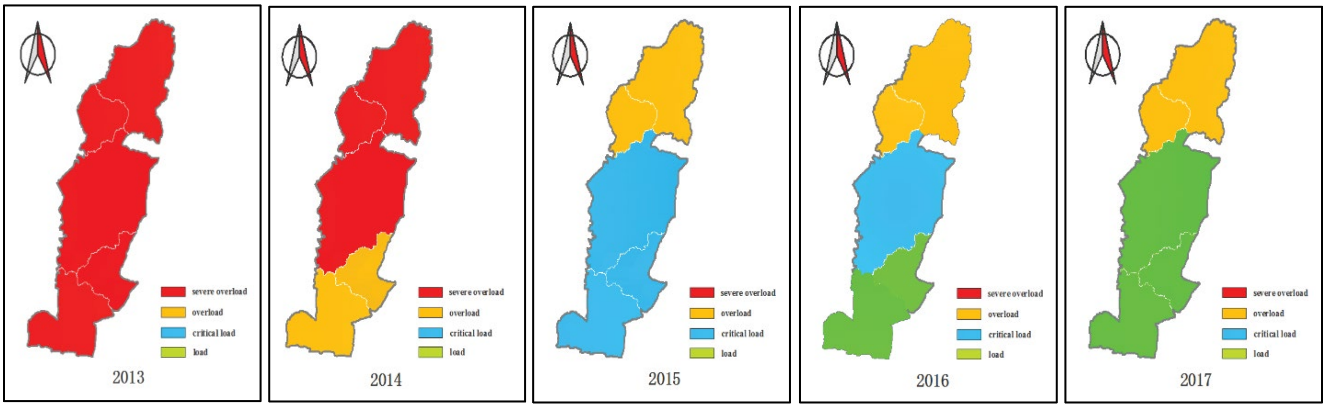

Fig. 1. Comprehensive evaluation results of WRCC in Dagong Yellow.

the production, living, and ecological water use in Dagong Yellow River Diversion Irrigation District should be rationally and efficiently utilized, and the ecological construction should be strengthened to ensure the sound operation of the "socio-economic-water resources-ecological environment" complex large-scale system. In addition, the focus should be laid on the research work of calculating the weights of evaluation indexes in the future research, in order to better balance the influence of subjectivity and objectivity on the weights of evaluation indexes, so as to improve the reliability of evaluation results and make the research conclusions more practical.

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