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Integration of fuzzy theory and multi-hierarchy comprehensive index system for health assessment of water environmental ecosystem

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ABSTRACT

Ecosystem health assessment is an effective way to cope with water pollution, environmental degradation and operation deterioration caused by human activities. Due to the complexity of water environmental ecosystem and the uncertainty of indicators, fuzzy theory improved approach for Multi-Hierarchy Fuzzy Comprehensive Evaluation (MHFCE) method is proposed in reservoir assessment. In the traditional MHFCE, the importance scale and membership degree of indicators are easily impacted by personal experience and subjective consideration, 0–1 scale is present in the process of weights calculation which avoids linguistic uncertainty when making comparison. Moreover, trapezoidal membership function and triangular membership function are presented in the process of fuzzy mapping in this method. A model application has been made in Lianhe Reservoir in Dongjiang Basin, South China, and it is concluded that reservoir assessment value belongs to the second lever of reservoir health. Overall, the improved MHFCE method provides better reservoir assessment to support reservoir management decisions with the decrease of uncertainty and increase of robustness.

Keywords: Fuzzy theory; MHFCE method; Ecosystem health assessment; Lianhe Reservoir

1. Introduction

Throughout China, reservoir ecosystem has experienced degradation to varying extents due to human activities, and become one of the most threatened ecosystems [1,2]. Reservoir ecosystem health is influenced by multiple ecological factors that need to be balanced [3]. Currently, many reservoirs are suffering water pollution, environmental degradation and operation deterioration. An increasing number of studies have shown that ecosystem health assessment is one of the vital tools for water resource management and sustainable development of river basins [4,5]. Considering nutrient and heavy metal contamination in reservoir, previous studies have focused on water quality assessment and much legislation has been developed in order to improve the water quality [6–10]. Also, flow regime characteristics play an important role in ecosystem health of reservoir, the relationships between flow and ecological processes need to be understood to guide the operation of dam and floodgates, and to achieve ecological restoration and improvements in reservoir health [11,12]. Recently, combination of rapid urbanization and climate change poses the threat to ecosystem health assessment [13,14].

However, ecosystem health is a widespread problem in river, lakes and reservoirs. Since the adoption of European Water Framework Directive (WFD) in Europe, much progress has been made in studying the ecosystem health of reservoir to provide scientific and technical support for

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water resource management [15–17]. Many ecological risk assessment methodologies have been developed over the last 20 years. Indicator species assessment is the method which uses multiple biological quality elements to assess ecological status of river, such as macrophytes, fish, diatoms, macro invertebrates [18,19]. Previously, researchers often investigated the total number of species to assess the river health [20,21]. However, sustainable management of freshwater resources relies on the continuous monitoring of species. Recently, a number of studies have used trait-based metrics in reservoir ecosystem assessment to present the higher sensitivity to human pressures [22,23]. These studies show that biological responses detected the reservoir degradation in ecosystem health assessment. At the same time, integrated indices assessment has demonstrated as a useful tool in environmental management and decision making of reservoir assessment. A great number of multi-criteria decision analysis methods have been proposed for environmental and ecological issues, such as TOPSIS, AHP [24–26], they help decision-maker to organize the problems better, and carry out a more efficient and overall analysis. With the aim of developing an overall strategy for protecting reservoir ecosystem heath, integrated indices assessment should balance the ecosystem services, the continued destruction of ecosystems, also the rapid increase in human activities. To sum up, the methods of integrated indices assessment are mainly divided into three categories: fuzzy comprehensive method, integrated health index method, and integrated index system method. However, it has been widely recognized that uncertainty is still the main difficult in the procedure of multi-criteria decision analysis methods.

This paper presents the analyses undertaken to assess ecosystem health of Lianhe Reservoir in Dongjiang Basin, South China using fuzzy theory. Firstly, we identified the ecological risk by the P-S-R conceptual model to establish a comprehensive index system for reservoir health assessment. Then the comprehensive assessment method of reservoir ecosystem health, including fuzzy set and Analytic Hierarchy Process (AHP), was developed through determining the weight sets of indicators and the membership degree. Finally, a model application was made in Lianhe Reservoir to assess ecosystem health.

2. Methodology

Multi-hierarchy fuzzy comprehensive evaluation (MHFCE) is an advanced method integrating fuzzy theory and analytic hierarchy process (AHP) relationship for the multi-criteria decision-making problem. Based on the risk identification of ecosystem health assessment, the weights of risk indexes are improved by applying fuzzy-analytic hierarchy process (FAHP), while the comprehensive risk assessment value is calculated based on fuzzy comprehensive evaluation (FCE).

2.1. Risk identification of ecosystem health assessment

The indicators of reservoir health assessment are referred to natural and social factors based on the concept of health ecosystem which means non-disease, stable, sustainable, self-recoverable and self-adjustable. Reservoir with multi-benefits of flooding, irrigation, electricity and urban water supply, is one of the efficient method to better use water resource under the background of spatio-temporal difference. The reservoir health assessment is consist of multi-dimensions, such as dam safety, water quality, hydrology, ecology and social function, so, 12 indicators are selected in this study (Table 1). This index system is consisted of three layers, i.e., the first Object layer is the comprehensive index of ecological health assessment (A); the second is the Items layer, including pressure system (B1), State system (B2) and response system (B3); and the third is the Indicators layer (C1, C2, C3,……C12), by which the multi-hierarchy system of analytic hierarchy process is determined. We divided the comprehensive index of ecological health assessment into five levers, including Very healthy (I), Healthy (II), Sub-healthy (III), Unhealthy (IV), and Sick (V). Each evaluation indicator is divided into five statuses, which corresponds to the assessment comprehensive index levers.

2.2. Determining weights by FAHP

Fuzzy-analysis hierarchy process (FAHP) is a systematized and hierarchical technique for complex decision-making. It is an improved model of AHP [27], and

Table 1
Comprehensive index system of reservoir health assessment

Object layer	Items layer	Indicators layer	Unit	(I)	(II)	(III)	(IV)	(V)
The comprehensive index of ecological health assessment (A)	B1	Probability of flood control (C1)	1	>0.95	0.95	0.7	0.6	<0.6
		Water resource utilization rate (C2)	%	>30	30	20	10	<10
		Hydro-project quality coefficient (C3)	1	<0.1	0.1	0.3	0.5	>0.5
		Dam safety coefficient (C4)	1	>1.3	1.3	1.25	1.2	<1.2
	B2	Reservoir vegetation rate (C5)	%	>35	35	20	15	<15
		Biodiversity index (C6)	1	>3	3	1.5	0.5	<0.5
		Probability of water storage (C7)	%	50	40	30	20	10
		Variation of discharge inflow (C8)	%	<10	20	30	40	50
		Reservoir nutrition index (C9)	1	0–20	20–50	50–60	60–80	80–100
		Reservoir water quality index (C10)	1	<0.1	0.2	0.4	0.75	1.0
	B3	Water quality of water supply rate (C11)	%	100	75	60	25	0
		Amount of available water supply (C12)	m^3	>1500	1500	750	300	<300

has been extensively used in many research fields [28–30]. The main process of FAHP is to determine the relative importance using fuzzy sets through pairwise comparison on the basis of the assessment index system, and to establish comparison matrix andcalculate the relative weights with mathematical method layer to layer, finally to obtain the comprehensive index value in the object layer. The proposed FAHP procedure of reservoir health assessment is described as follows.

Based on the assessment index system in Table 1, the comparison matrix $X_{n\times n}$ is given below:

$$X_{n\times n} = \begin{array}{c} \\ X_1 \\ X_2 \\ \vdots \\ X_n \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \cdots & X_n \end{array} \\ \begin{bmatrix} 1 & x_{12} & \cdots & x_{1n} \\ x_{21} & 1 & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{n1} & x_{n2} & \cdots & 1 \end{bmatrix} \end{array}$$

where x_{ij} (i = 1, 2…m) represents pairwise relationship of X_i and X_j in the same layer.

To make a quantitative comparison, numerical value criteria of comparison matrix are proposed to use the most popular Satty scale of 1–9. However, experts' preferences are always uncertain and it is a difficult work to give a quantitative comparison from 1 to 9 because of the fuzzy description of scale value. Some improved scale criteria have been extensively studied, 0–1 scale is one of the convenient methods avoiding linguistic uncertainty when making comparison, it is much easier for people to show the message whether A or B is more important (Table 2).

The procedure of 0–1 scale is to identify the importance between two indicators, then the quantitative comparisons is converted into 1–9 scale by Eq. (1) indirectly. Table 3 gives the rules of 0–1 scale conversion into 1–9 scale.

Table 2
0–1 scale

Scale value	Meaning
0	X_i is less important than X_j
0.5	X_i and X_j are of equal importance
1	X_i is more important than X_j

Table 3
Conversion between 0–1 scale and 1–9 scale

Scale	x_{ij}'
1	0–1
2	1–2
3	2–3
4	3–4
5	4–5
6	5–6
7	6–7
8	7–8
9	8–9

$$x_{ij}' = \begin{cases} \dfrac{9(r_i - r_j)}{n}, & r_i > r_j \\ 1, & r_i = r_j \\ \left[\dfrac{9(r_i - r_j)}{n}\right]^{-1}, & r_i < r_j \end{cases} \tag{1}$$

where $r_i = \sum_{i=1}^{n} x_{ij} i = 1,2,\ldots n$

When constructing comparison matrix, people make a quantitative decision of importance between two indicators, the inconsistency of the experts' preference may exist. Consistency index (CI) and consistency ratio (CR) are defined to estimate the consistency of pairwise comparisons.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{2}$$

where λ_{max} is the maximum eigenvalue of comparison matrix, n is the dimension of the comparison matrix.

$$CR = \frac{CI}{RI} \tag{3}$$

where RI is the mean random consistency index (Table 4).

The closer CR to zero, the greater the consistency is. If CR less than 0.10, the consistency is acceptable, otherwise, it is compulsive to redo comparisons and the comparison matrix should be revised.

Supposing $W = (w_1\ w_2\ w_3\ \ldots w_n)$ is the weight set of indicators, $0 < w_i < 1$, $\sum wi = 1$, to solve characteristic vectors of comparison matrix by the following equation,

$$X_{n\times n} \cdot W = \lambda_{max} \cdot W \tag{4}$$

Normalization is applied on the characteristic vectors W, and weight set w is calculated.

2.3. Determining membership degree by fuzzy theory

Since the fuzzy sets theory was first introduced [31], the concept of membership degree is proposed and it is described by a numeral value in the interval [0,1]. When membership U(x) is near "1", it is said that there is a high

Table 4
Relationship between dimension and RI

Dimension	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45

possibility that element "x" belongs to set "U"; when the membership U(x) is close to "0", there is a low possibility that element "x" belongs to set "U".

$$\mu(x): x \to \mu_U(x)$$

According to characteristics of reservoir health assessment, 12 indicators in assessment index system are quantitative, trapezoidal membership function and triangular membership function are present in this study. When indicator value increases, the assessment result is more satisfied, left semi-trapezoidal membership function is adopted; conversely, right semi-trapezoidal membership is adopted.

2.4. Calculation of assessment result by FCE

Fuzzy comprehensive evaluation (FCE) assesses the risk layer by layer [Eq. (5)], the correction indicator in the k-th layer is considered as the membership degree of the k–1 layer.

where W_i (i = 1, 2…k) is weight vector, R_i (i = 1, 2…k) is membership degree matrix, S is the assessment result.

3. Study region and data sources

As a demonstration, we applied the method to Lianhe Reservoir in Dongjiang Basin which is one of the main tributary of Pearl River. Lianhe Reservoir (Fig. 1), with the normal storage of 6.083×10^7 m^2, mean water depth of 30.1 m and catchment area of 110.8 m^2, is responsible for drinking water supply to Huizhou, Guangdong Province. It also plays the roles of agricultural irrigation and hydro power, yet a challenge is faced in ecosystem health of Lianhe Reservoir due to human activities. Among the 12 indexes, C1 was obtained from design materials, C2 and C7 were obtained from historic data, C3 and C4 were obtained from field survey, C5, C6, C8, C9, C10, C11 and C12 are obtained from measure data.

4. Results and discussion

Step 1. Calculation of weight. To perform the pair-wise comparisons, the questionnaire had been done by decision-makers. The comparison matrix established on the 0–1 scale, then converted to Satty's comparison matrix. The weight vectors are calculated by Eq. (4) (Table 5).

Step 2. Determination of membership degrees. Quantitative indicators and qualitative indicators are involved in this comprehensive index system of reservoir system assessment. Because of their special characteristics, we adopted different methods to obtain their membership degrees respectively. Quantitative indicators, such as C1, C2, C5, C6, C7, C9, C10, C11, C12, whose membership functions can be determined by fuzzy theory. In this paper, we using semi-trapezoidal membership function to describe the minimum lever and maximum lever, and using triangular membership function to describe the medium levers. Otherwise, the membership degrees of qualitative indicators can be determined by expert judgment. In order to ensure that results are more reliable, we select experts according to the following: firstly, the selected experts should be associated

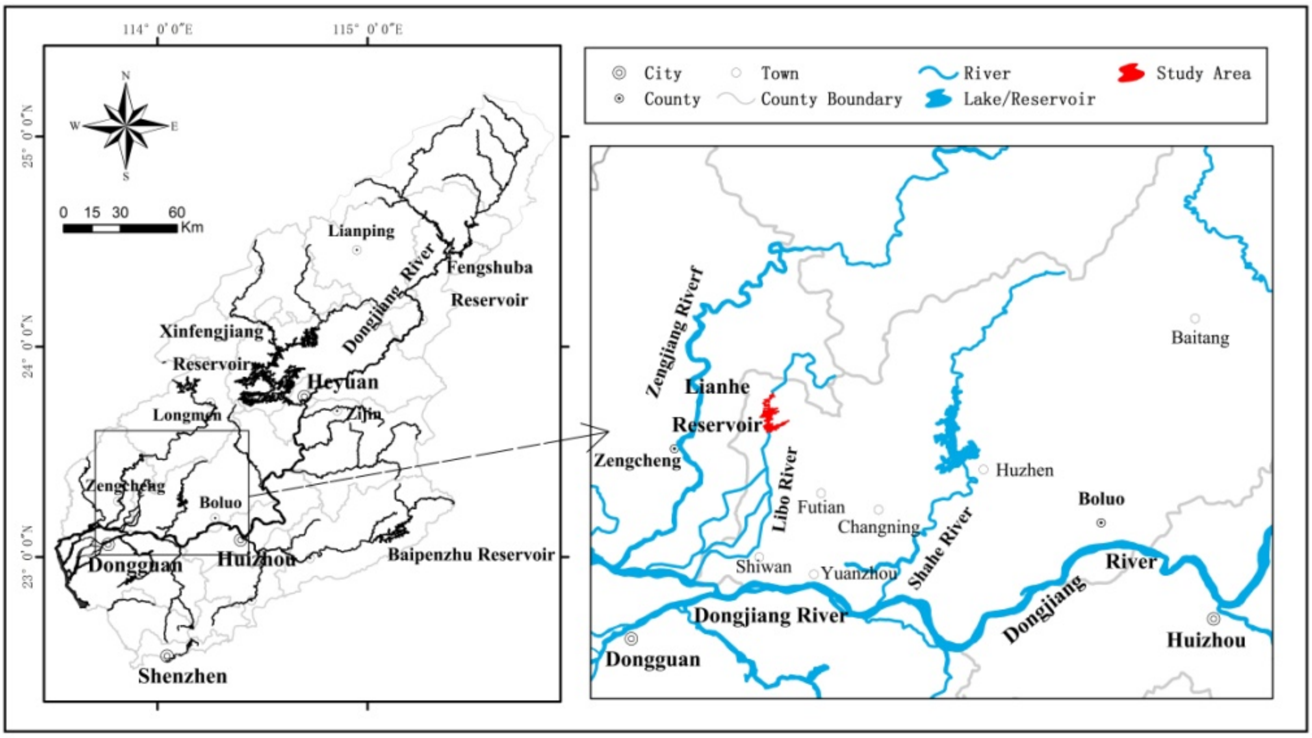

Fig. 1. Map of study region.

Table 5
Summary of the measured weights

Items layer		Indicators layer		Values of Lianhe Reservoir	Very healthy (I)	Healthy (II)	Sub-healthy (III)	Unhealthy (IV)	Sick (V)
B1	0.3333	C1	0.1136	0.997	0.1880	0.8120	0	0	0
		C2	0.0472	25	0	0.5000	0.5000	0	0
		C3	0.4196	qualitative	0.0400	0.8680	0.0920	0	0
		C4	0.4196	qualitative	0.3850	0.6150	0	0	0
B2	0.3333	C5	0.1478	33	0	0.8667	0.1333	0	0
		C6	0.0799	2.1	0	0.4000	0.6000	0	0
		C7	0.2685	43	1.0000	0	0	0	0
		C8	0.4149	qualitative	0	0.5500	0.4500	0	0
		C9	0.0445	23	0.4737	0.5263	0	0	0
		C10	0.0445	0.28	0	0.6000	0.4000	0	0
B3	0.3333	C11	0.8333	73	0	0.8667	0.1333	0	0
		C12	0.1667	672	0	0	0.8267	0.1733	0

Table 6
Membership degrees of C3 by expert judgments

Expert judgments	Very healthy (I)	Healthy (II)	Sub-healthy (III)	Unhealthy (IV)	Sick (V)
Decision-maker 1	0.08	0.92	0	0	0
Decision-maker 2	0	0.89	0.11	0	0
Decision-maker 3	0.03	0.97	0	0	0
Decision-maker 4	0.09	0.91	0	0	0
Decision-maker 5	0	0.88	0.12	0	0
Normalized value	0.04	0.868	0.092	0	0

Table 7
Assessment results of Lianhe Reservoir

Object layer	Very healthy (I)	Healthy (II)	Sub-healthy (III)	Unhealthy (IV)	Sick (V)	Status
S	0.1631	0.6328	0.1944	0.0096	0	Healthy

with reservoir ecosystem healthy. Secondly, they should participate in the government officials. Third, in order to enhance the efficiency, the number of the experts should be limited. Consequently, five decision-makers were questioned. They individually give the scores of the risk levels, and the scores are then normalized to obtain the final value of the membership degrees (Table 6).

Step 3. Calculation of final results. In ecosystem health assessment, our goal is to evaluate the health status through analysis. By using Eq. (5), FCE is performed, and the assessment result of Lianhe Reservoir is obtained in Table 7 and Fig. 2. According to the maximum membership degree principle, the second level "healthy (II)" is the ecosystem health assessment result of Lianhe Reservoir which has the maximum membership degree of 0.6328. It can be concluded that Lianhe Reservoir is a healthy reservoir according to our ecosystem assessment.

The main purpose of this study is to determine whether reservoir ecosystem is healthy, and which health level it is in. Lianhe reservoir is in the level of healthy, however there is the probability of 0.1944 in the level of sub-healthy, and 0.1631 in the level of very healthy. In addition to the reservoir ecosystem, the sub-system can also be assessed by P-S-R concept model. Regarding the membership degrees in items layer, we infer that Pressure system, statement system, and response system are all in the second level of reservoir health ecosystem. The weight of hydro-project quality coefficient and dam safety coefficient are obviously high in pressure system, which indicates they play the more important role. Similarly, probability of water storage and variation of discharge inflow are the main indicators in state system, it is water quality of water supply rate in response system. We determine that maximum membership degree of three indicators (water resource utilization rate, biodicersity index, Amount of available water supply) are in the level of sub-healthy, which are 0.5, 0.6, 0.8267 respectively, lower than the overall assessment result of Lianhe Reservoir. It is a scientific suggestion for decision-maker to pay

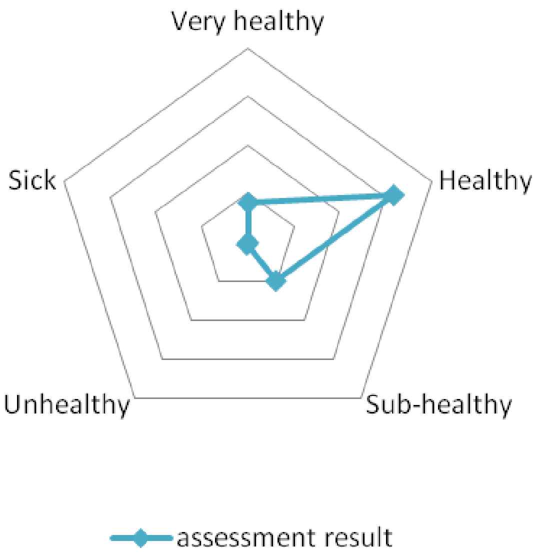

Fig. 2. Assessment result of Lianhe Reservoir.

more attention on these three indicators, so that the ecosystem health of Lianhe Reservoir will be improved.

Moreover, the process of ecosystem health assessment involves multiple indexes with obvious uncertain characteristics, this method focus on the uncertainty of indicators, included the quantitative and the qualitative. Multi-hierarchy comprehensive assessment has an innovation in determining of weight and membership degree by fuzzy sets. A comprehensive index system has been constructed to set up the comparison matrix. Considering the uncertainty in quantitative comparison, we established the pair-wise relationship layer by layer and ran the synthesis model of Fuzzy theory and AHP on the 0–1 scale as an improved Satty's scale. Meanwhile, it is properly to identify the importance of assessment indicators, and to improve reliability of the weight vectors. Due to the different operation status of reservoir, the pair-wise comparisons will be revised, and the weight sets of indicators could be different. By demonstrating the membership degrees in indicators layer, the probability of indicators in five different health levels is showed, which reduces the uncertainty of indicators and improves the robustness of assessment results.

5. Conclusion

Using multi-hierarchy fuzzy comprehensive evaluation (MHFCE) method, the ecosystem health of Lianhe Reservoir in Dongjiang River was evaluated. Appropriate indexes, careful pair comparisons, and membership analysis are important for ecosystem health assessment. The following conclusions have been drawn in this study:

(1) MHFCE is a powerful technique to solve multi-hierarchy decision-making problems. At each hierarchy, the assessment can be regarded as a multi-indexes determination process, the weight vector in the upper hierarchy is initially provided by the iteration process of FCE in the lower hierarchy. More than one participant in the membership degree determination process makes ecosystem health assessment to be treated as a group decision-making problem. Combining expert knowledge, data investigation and mathematic procedure, MHFCE also leads to the improvement of the quality of the group decision made.

(2) The proposed procedure for multi-hierarchy group decision-making can be applied to support ecosystem health assessment, a case study of Lianhe Reservoir in China is used to demonstrate that the approach is feasible and efficient in practice. This method has been recently developed to use in a fuzzy decision process, furthermore, it can be adopted to various applications in water resource management.

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Table 8
Membership degrees in items layer

Membership degrees	Items layer	Very healthy (I)	Healthy (II)	Sub-healthy (III)	Unhealthy (IV)	Sick (V)
R	S1	0.1997	0.7381	0.0622	0	0
	S2	0.2896	0.4384	0.2721	0	0
	S3	0	0.7222	0.2489	0.0289	0

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