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Environmental impact evaluation model of dam breach — considering the uncertainty feature of environment

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ABSTRACT

The environmental impact of dam breach has the features of complexity and uncertainty. There is a lack of systematic and comprehensive research on the environmental impact of dam breach in China. Considering such fuzziness of environment evaluation and the lack of precise data, this work chooses the method of multi-index comprehensive evaluation. Targeting to solve the uncertainty problem of weight calculation and evaluation model, this work introduces the statistic cloud theory to calculate the weight and variable fuzzy set theory to evaluate the environmental impact. We select seven environmental impact factors, including channel morphology, vegetation coverage, water and soil environment, biodiversity, human ecology, and industrial pollution, are selected to construct the evaluation index system and construct the value standard of them. The models are applied to the dam of Shaheji Reservoir in China. The results show that the environmental impact degree of the reservoir member an extremely serious grade mostly, reaching 0.589. Compared with the evaluation results already done, the result of the proposed models shows that the models are reasonable and scientific, which provides a new method for environmental impact assessment of dam breach considering the uncertainty feature of the environment.

Keywords: Environmental impact; Dam breach; Cloud theory; Variable fuzzy set

1. Introduction

According to the definition of international dam conference-ICOLD in 2000, the risk of a dam is determined both by the risk probability of dam-failure and its risk consequence. As one of the main parts of the risk consequence analysis of the dam breach [1], environmental impact evaluation has features of diversity, uncertainty, and variability, resulting in less quantitative research than the study of life loss and economic loss [1–4]. The research of the environmental impact of dam breach is beneficial to the decision-makers not only to understand the risk level of the dam more comprehensively but also to make more scientific risk management decisions [5]. The environmental impact assessment and environmental management plans are both used to evaluate the environmental impact [6]. Uncertainties such as dynamics, linkage, and ambiguity are typical characteristics of environmental systems [7,8]. Such uncertainties often

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come from multiple factors and multiple variables, which could be well dealt with and processed by establishing the mathematical model [7,9,10]. A fuzzy method is widely used to solve environmental assessment problems, such as the typical fuzzy model [11] and the Nero-fuzzy method [12]. The existed methods did not concern the uncertain feature of the environmental system and lead to problems in weight calculation and impact evaluation process. This paper aims to introduce the statistic cloud theory (SCT) and variable fuzzy set theory (VFST) to solve the uncertainties of expert weighting and model output respectively. In this paper, the integrated environmental impact evaluation model concerning the uncertain features is established and applied in practical engineering for model validation.

2. Methods

2.1. Statistic cloud theory

The statistic cloud model, which was proposed by Professor Li [12,13] model of uncertainty transformation between a qualitative concept and quantitative numerical representation. It mainly reflects the ambiguity and randomness of the concept of things or human knowledge in the objective world and integrates these two together. Constituting the mutual mapping between qualitative and quantitative, a cloud generator is a key to its practical application.

Suppose a universe $U = \{x\}$, L is the language value of the link in U. The membership degree $R_L(x)$ of the element x in U to the qualitative concept expressed by L is a stable random number. The membership degree distributed in the universe of discourse is called the cloud model of membership cloud, which can be abbreviated as “Cloud” [13], which is shown in Fig. 1. The x and y axes are for the expected number and probability of distribution respectively.

$R_L(x)$ takes a value between 0 and 1, whereas the cloud represents the mapping from the universe U to the interval (0,1), that is, $R_L(x):U \to (0,1)$, $\forall x \in U$, $x \to R_L(x)$.

It can be seen that the qualitative concept to the quantitative value on the universe U is a one-to-many mapping relation, rather than a one-to-one relationship on the traditional fuzzy function. The degree of membership of x to L is a probability distribution, not a fixed value. The cloud model uses the expectation (Ex), entropy (En) and hyper entropy (He) as a whole to characterize an uncertain concept.

2.1.1. Expectation (Ex)

The mathematical expectation of cloud drop distribution in the universe of discourse, that is, the domain value corresponding to the centric of the area under the cover of the membership cloud, which is the domain value x of the degree of membership. Generally, it is the point most capable of characterizing the qualitative concept, reflecting the information center value of the corresponding fuzzy concept.

2.1.2. Entropy (En)

A measure of the ambiguity of a qualitative concept, reflect the range of values that can be accepted by the concept in the universe U. In the statistic cloud model, entropy is mainly used to measure the ambiguity and probability of qualitative concepts, reflecting the uncertainty of qualitative concepts. The larger the entropy value is, the larger the range of values can be accepted by the concept and the more obscure the concept is. It embodies the flexibility of qualitative language.

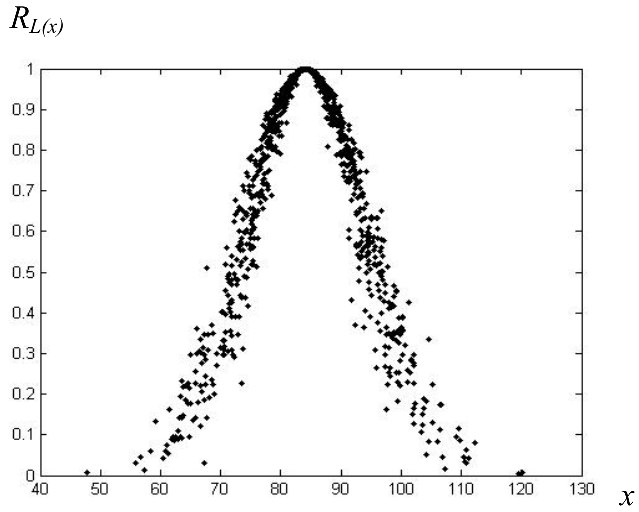

Fig. 1. Sketch map of a membership cloud.

2.1.3. Hyper-entropy (He)

The measure of entropy uncertainty, entropy of entropy, reflects the discreteness of cloud drops. When the hyper-entropy is larger, the dispersion of cloud droplets is greater, that is, the greater the randomness of the membership value is, and the greater the “thickness” of the cloud can be. When it is closer to the concept center or away from the center, the randomness is relatively small, which is similar to a person’s subjective feelings.

2.1.4. Cloud generator

Generator is the most basic cloud algorithm, which can achieve quantitative range and distribution rules from the qualitative information expressed in language value. Cloud generators are mainly divided into the forward cloud generator and the backward cloud generator. The conversion process from a qualitative concept to quantitative representation is conducted by the forward cloud generator; the conversion process from quantitative representation to qualitative concept is produced by the backward cloud generator.

2.2. Variable fuzzy set theory

VFST is established by Professor Shouyu Chen [14], based on the engineering fuzzy sets theory and the relativity of the fuzzy concept and dynamic variability. It is the breakthrough and development of classical and static fuzzy sets. The core concept of VFST includes the relative membership degree and relative difference degree, according to the definition given by Professor Shouyu Chen [15,16]: assuming that the opposite fuzzy concept (things and phenomenon) in the domain U, using $\tilde{A}$ and $\tilde{A}_c$ to represent attractive and repulsive property respectively. As for any element u in U, $u \in U$, in continuous axis relative membership function on a point of attraction and repulsion relative membership degree are $\mu\tilde{A}(u)$ and $\mu_{\tilde{A}c}(u)$, and $\mu_{\tilde{A}(u)} + \mu_{\tilde{A}c}(u) = 1$, calling $D_{\tilde{A}}(u)$ as the relative coefficient from u to $\tilde{A}$, among them:

$$D_{\tilde{A}}(u) = \mu_{\tilde{A}}(u) - \mu_{\tilde{A}}A(u) \quad (1)$$

According to VFST, relative coefficient model is:

$$\begin{cases} D_{\tilde{A}}(u) = \left(\dfrac{x-a}{M-a}\right)^{\beta}, x \in [a, M] \\ D_{\tilde{A}}(u) = -\left(\dfrac{x-a}{c-a}\right)^{\beta}, x \in [c, a] \end{cases} \quad (2)$$

Or

$$\begin{cases} D_{\tilde{A}}(u) = \left(\dfrac{x-b}{M-b}\right)^{\beta}, x \in [M, b] \\ D_{\tilde{A}}(u) = -\left(\dfrac{x-b}{d-b}\right)^{\beta}, x \in [b, d] \end{cases} \quad (3)$$

In the formula, x is the magnitude of any arbitrary point within the range; a and b are used to evaluate the interval of the upper and lower limits respectively; c and d stand for the variable range evaluation interval limits respectively; M is the relative membership degree matrix which is equal to the value of 1; β is a non-negative index, usually take $\beta = 1$.

3. Evaluation model of environmental impact of dam breach

3.1. Case study

This paper takes the Shaheji Reservoir in Anhui province, China as an example. Completed in 1979, Shaheji Reservoir is located in the west of Shahe town of Chuzhou city in Anhui province across the Chuhe tributary in the lower reaches of the Yangtze River. With a total capacity of 1.85 × 108 m^3, Shaheji Reservoir, belonging to type II reservoir, is mainly built for irrigation. Besides, it also has a comprehensive utilization such as flood control, water supply and so on. The normal water level of the reservoir is 40.50 m, the designed flood level is 42.35 m. There are residential and industrial areas downstream of the reservoir. A schematic diagram of the Shaheji Reservoir is illustrated as Fig. 2:

3.2. Index system of environmental impact assessment of dam breach

The construction of a dam breach environmental impact assessment index system is the basis and premise of the whole evaluation model. There are no uniform definitions for the meaning of various environmental impacts on dam breach [17–19]. According to the characteristics of dam breach behavior [20], we studied the possible effects of dam-break floods on different disaster-bearing bodies downstream and the environmental results, as shown in Fig. 3.

According to the previous research [21,22] and the principle of scientific, systematic, comprehensive and representative, we determine the channel morphology, water environment, soil environment, vegetation coverage rate, bio-diversity, human ecological environment, industrial pollution as 7 dam environmental impact evaluation indicators. This entire evaluation index can be classified into

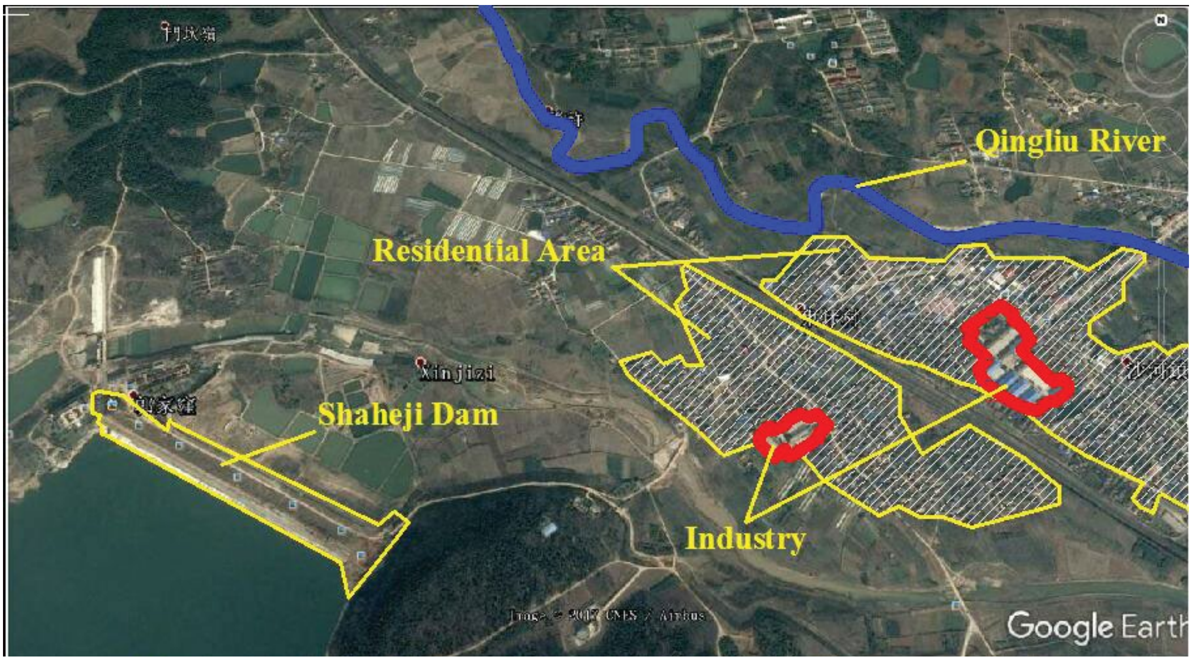

Fig. 2. Diagram of the Shaheji Reservoir.

different status to reflect their sensitivity to dam failure events respectively [23], which reflects the predictive nature of dam damage assessment of environmental impact. In this paper, a dam breach environmental impact assessment index system is established, as shown in Fig. 4.

3.3. Assessment level standard of environmental impact assessment of dam breach

This paper divides the seriousness of the impact into five grades, which in terms of "minor", to "extremely serious", and the indices standard of each grade are formulated accordingly. Among the seven indicators, the quantitative index "river morphology" is measured by the amount of rushing flood or sedimentation in a case area with given width and length, and the index "vegetation coverage rate" is calculated by "vegetation covering area and affected downstream area". The other qualitative indices adopt the method of dividing 0–100 by interval method for expert assignment, due to the difficulty of quantification. In the decision of the standards of water environment and soil environment, former researchers usually adopt a method of post-disaster evaluation of water quality or soil composition to conclude. But the method will not adapt to this research, because the dam failure environmental impact assessment is a kind of risk prediction system, which cannot confirm the change of the water quality and soil quality evaluation level before and after the dam failure. Another reason is the difficulty of simulating the influence of water environment and soil environment, so the data cannot be obtained directly and precisely. Therefore, based on the "Surface Water Environmental Quality Standard" [24] and "Soil Environmental Quality Standard" [25], we take environmental sensitivity or vulnerability as a standard for grading, for example, a higher original water environment or soil environmental quality indicates a higher vulnerability of the downstream to dam breach, and a higher corresponding risk level. Each evaluation indicators corresponding to the range of values are shown in Table 1.

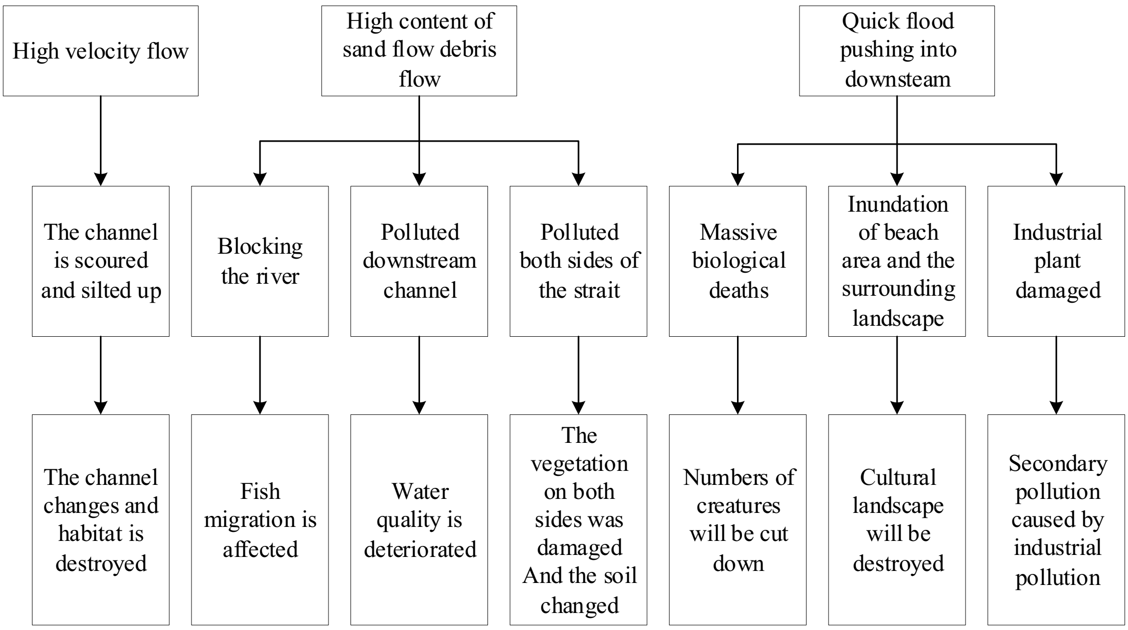

Fig. 3. Influence of dam breach flood on downstream.

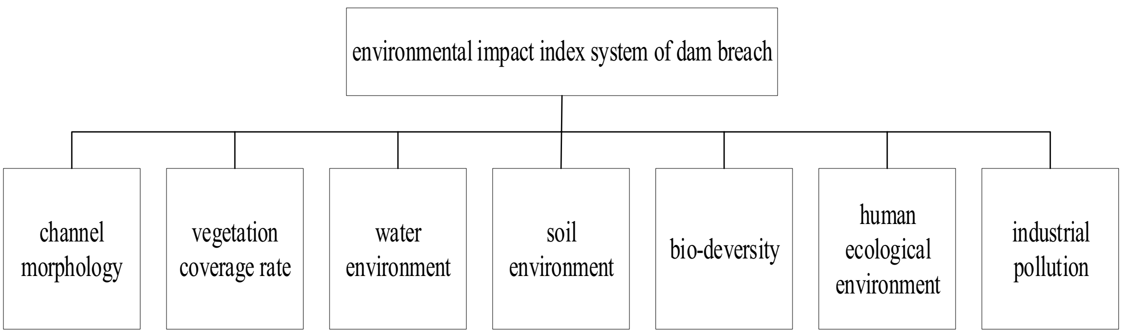

Fig. 4. Dam environmental impact evaluation index system.

Table 1
Dam breach environmental impact assessment indicators standard

Impact degree		Minor	General	Medium	Serious	Extremely serious
Qualitative index		(0,25)	(25,45)	(45,65)	(65,85)	(85,100)
Quantitative index	Vegetation cover rate (land damage rate and severity)	(0,0.2)	(0.2,0.4)	(0.4,0.6)	(0.6,0.8)	(0.8,1)
	River morphology (unit length and width of erosion or siltation volume, ($m^3\ m^{-1}\ m^{-1}$)	(0,0.2)	(0.2,0.5)	(0.5,1)	(1,2)	(2,10)

3.4. Evaluation model and calculation steps

The evaluation process is shown in Fig. 5, and the evaluation steps are as follows:

3.5. Determination of the weight of the index

Suppose there are n indicators (column vectors) and m experts (row vectors). Each indicator computes the expectation and variance according to the cloud model. Statistical formula for calculating the kth indicator is:

$$Ex_j = \overline{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij} \quad (i = 1,\ldots,\ m;\ \ j = 1,\ \ldots,\ n) \tag{4}$$

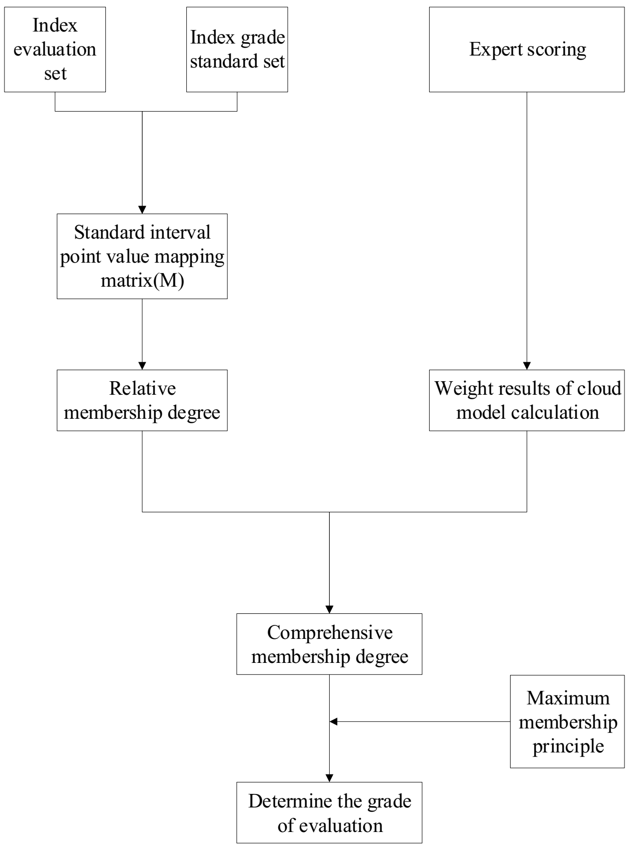

Fig. 5. Diagram of the evaluation process.

$$En_j = \sqrt{\frac{\pi}{2}}\frac{1}{m}\sum_{i=1}^{m}\left|x_{ij} - Ex_j\right| \quad (i = 1,\ldots,m;\ j = 1,\ldots,n) \tag{5}$$

According to the principle of entropy method that the more different is between the data, the lower information it should carry. We established the weight calculating model as:

$$\hat{\omega}_j = \begin{cases} \dfrac{Ex_j}{\ln\left(1+En_j\right)+1} \times \dfrac{1}{\sum_{j=1}^{n}\dfrac{Ex_j}{\ln\left(1+En_j\right)+1}} & \left(En_j \neq 0\right) \\ \dfrac{Ex_j}{\sum_{j=1}^{n} Ex_j} & \left(En_j = 0\right) \end{cases} \tag{6}$$

If the cloud entropy En_j is not equal to 0, the formula of the weight is revised and the cloud entropy is involved in the calculation. The larger the cloud entropy, the more divergence of opinions the expert has on the index, so the weight of the index should be reduced. The smaller the entropy is, the smaller the expert's disagreement on the indicator, so the weight of the indicator should be increased.

3.6. Constructing the set of evaluation value and the standard value of indicators

Let the set $T = \{t_1, t_2, t_3, t_4, t_5, t_6, t_7\}$ and the set P denote the set of evaluation indices and the evaluation level standard set, respectively.

$$P = \begin{bmatrix} X_{10} & X_{11} & \cdots & X_{1k} \\ X_{20} & X_{21} & \cdots & X_{2k} \\ \vdots & \vdots & & \vdots \\ X_{q0} & X_{q1} & \cdots & X_{qk} \end{bmatrix} \tag{7}$$

Q represents the evaluation value of each index; X_{qk} denotes the kth evaluation index corresponding to the q value of the evaluation criteria, the specific threshold of the evaluation standard in Table 2.

Table 2
Evaluation values of indicators of Shaheji Reservoir dam

Assessment index	Magnitude	Evaluation value
Channel morphology	Severely damaged river	1.8
Water environment	Water quality grade decline	49.5
Soil environment	Soil quality grade decreased	91.6
Vegetation coverage rate	Surface woodland, large area is damaged	0.78
Biodiversity	General animal and plant	13.3
Human ecological environment	Municipal environment has been damaged	27.8
Industrial pollution	Large-scale chemical and pesticide plants factories	84.1

3.7. Determination of the standard interval point

3.7.1. Mapping matrix

M_{ih} is the point value when indicator $i (i = 1,2,\ldots q)$ in the standard interval (a_{ih}, b_{ih}) has a relative membership degree of 1 to the level h, M_{ih} can be determined based on the physical meaning and the actual situation. Since M_{ih} $(h = 1, 2,\ldots, r)$ is an important parameter, for level 1 $M_{i1} = a_{i1}$, for level r $M_{ir} = a_{ir}$, for intermediate level l, when r is odd, $M_{i1} = (a_{i1} + b_{i1})/2$. The general model of point value M_{ih} satisfying the above conditions is:

$$M_{ih} = \frac{r-h}{r-1} a_{ih} + \frac{h-1}{r-1} b_{ih} \tag{8}$$

In the formula: for $h = 1$, $M_{i1} = a_{i1}$; for $h = r$, $M_{ir} = a_{ir}$, for $h = l = \frac{r+1}{2}$, $M_{il} = \frac{a_{il} + b_{il}}{2}$. By Eq. (8), matrix $M = (M_{ih})$ can be obtained from the matrix P.

3.8. Determination of relative membership degree of the indicator x_{ij} to each level

If the evaluation indicator x_{ij} of the sample u_j falls into $(M_{ih}, M_{i(h+1)})$, the interval between the adjacent two levels of the matrix M, level h and level $(h + 1)$, then the relative membership degree of indicator i to level h can be calculated by the following formula:

$$\begin{cases} \mu_{ih}\left(u_j\right) = 0.5\left(1 + \dfrac{b_{ih} - x_{ij}}{b_{ih} - M_{ih}}\right), & x_{ij} \in \left[M_{ih}, b_{ih}\right] \\ \mu_{ih}\left(u_j\right) = 0.5\left(1 + \dfrac{b_{ih} - x_{ij}}{b_{ih} - M_{i(h+1)}}\right), & x_{ij} \in \left[b_{ih}, M_{i(h+1)}\right] \\ \mu_{ih}\left(u_j\right) = 1, & x_{ij} = M_{ih} \end{cases} \tag{9}$$

According to physical concept, when indicator i is less than level h and greater than level $(h + 1)$, its relative membership should be equal to 0, that is:

$$\mu_{i(<h)}\left(u_j\right) = 0, \mu_{i(<(h+1))}\left(u_j\right) = 0 \tag{10}$$

Combining with the evaluation index weight vector to determine the evaluation of the object and the evaluation level of the degree of integration μ_h:

$$\mu_h = \sum_{i=1}^{7} \omega_i \mu_{ih} \tag{11}$$

Where: ω_i denotes the weight of the evaluation of indicator i.

3.9. Determination of the evaluation level

According to the principle of maximum relative membership degree, the relative membership degree of each evaluation grade is compared, and the dam environmental impact assessment rating is determined.

4. Results and discussion

To verify the rationality and validity of the comprehensive evaluation model of variable fuzzy sets, and to make a comparative analysis of the evaluation results, this paper uses the data of reference [26], evaluates the environmental impact assessment model of dam-breach, and compares it with the results of fuzzy comprehensive evaluation. The evaluation values of indicators are shown in Table 2.

From the Eqs. (5)–(8), and the experts' scoring process [27], the weight of the environmental impact index is calculated and shown in Table 3:

According to the score of the factor and their weight, we adopt the Eqs. (9)–(12) to get the calculation results of comprehensive membership degree, comparing with outcome of fuzzy mathematics theory evaluation method as shown in Table 4:

According to the principle of maximum relative membership degree, it is concluded that the environmental impact of the dam in Shaheji Reservoir is "extremely serious".

It can also be seen from Table 4 that the evaluation results of this model are basically in agreement with the results of fuzzy mathematics evaluation methods. The concepts and definitions of risk indicators and the classification of risk grade standards are relatively vague. Therefore, the whole dam-breach disaster environmental impact system embodies the characteristics of randomness, fuzziness, and variability. In the theory of fuzzy mathematics, it is an attempt to use precise mathematical language to express the concept of fuzziness. However, there are problems of uniqueness and absoluteness. It cannot fully reflect the transitional nature of the intermediary of indicators, which directly affects the application of fuzzy mathematics in practice. The theory of variable fuzzy sets better reflects the relativity and dynamic variability of fuzzy concepts avoids the static problem of membership functions in the theory of fuzzy sets and better solves the problems such as the difficulty of distinguishing between adjacent two types of differences, the difficulty of reflecting the uncertainty in the evaluation process and the incompatibility of evaluation indicators using fuzzy mathematics. The relative membership degree avoids the static problem of the membership function in the fuzzy mathematics theory, and better improves the fuzzy mathematics. Furthermore, the calculation model used in this paper considers the uncertainty of the model design comprehensively and reflects the environmental impact level of dam breach scientifically.

5. Conclusion

Dam breach is a kind of low probability and high loss risk event with uncertainty. The grading evaluation standards of many indicators are fuzzy, and there are many uncertainties in the scoring process. In this paper, 7 indicators are selected as the indices of dam breach environmental impact according to the risk sensitivity of dam breach and the strength of risk-bearing capacity. We used SCT to calculate the weight distribution of the indicators. In order to overcome the problem of absoluteness of membership degree of fuzzy mathematics, VFST is introduced, which more can reflect the uncertainty of environment, to calculate the environmental impact of dam breach. While respecting the subjective and objective opinions of expert weight evaluation, this paper takes into account the randomness and fuzziness of scoring.

Table 3
Dam environmental impact evaluation index weight

Evaluation index	Weight value
Channel morphology	0.068
Water environment	0.260
Soil environment	0.500
Vegetation cover	0.078
Biodiversity	0.052
Human ecological environment	0.017
Industrial pollution	0.025

Table 4
Evaluation results comparison

Method	Fuzzy mathematics theory evaluation method	This paper
Minor	0.036	0.0419
General	0.121	0.0986
Medium	0.155	0.1885
Serious	0.337	0.2705
Extremely serious	0.351	0.5890

Furthermore, in the process of model output, the uncertainty problem of environmental impact is well solved by using variable parameter combination after analyzing the stability of multiple calculation results, which improves the objectivity and accuracy of model calculation results. The application of the model to the Shaheji Reservoir dam shows that (1) the environmental impact degree of the reservoir member the extremely serious grade mostly, reaching 0.589. (2) The result of the environmental impact calculated by SCT-VFST is consistent with the one calculated by the fuzzy mathematics method. (3) The established model can well deal with the uncertainty in the process of evaluating the environmental impact of dam breach. Therefore, it is reasonable and feasible to apply the SCT-VFST evaluation model to the dam environmental impact assessment, which provides a new method for dam environmental impact assessment.

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Author contributions

Conceptualization: W.L. and W.G.; Methodology-W.L.; Validation-W.G., W.L. and Z.L.; Formal analysis-W.L.; Resources-W.G.; Data curation-W.L.; Writing—original draft preparation-W.L.; Writing—review and editing-W.G. and Z.L.; Visualization-W.L.; Supervision-Z.L.; Project administration-Z.L. and W.G.; Funding acquisition-Z.L. and W.G.

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