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Analysis of Social and Environmental Impact of Earth-Rock Dam Breaks Based on a Fuzzy Comprehensive Evaluation Method

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Abstract: A large proportion of the dams in China are earth-rock dams. Regarding the well-studied loss of life and economic consequences due to dam breaks, this paper introduces the causes and modes of earth-rock dam breaks and the corresponding dam-break losses in terms of the social and environmental aspects. This study formulates the evaluation index system and criteria of earth-rock dam breaks' impact on society and the environment based on a fuzzy comprehensive evaluation method. The results show that the evaluation grade of the social and environmental impact of the dam break of the Liujiatai Reservoir was "serious". Therefore, similar dams in China should take corresponding measures in advance to reduce the social and environmental impact of earth-rock dam breaks.

Keywords: earth-rock dam break; social and environmental impact; evaluation; fuzzy comprehensive evaluation method

1. Introduction

Earth-rock dams account for the largest proportion of all kinds of dams in China and are the most common type of dams that experience dam breaks. Once a dam break occurs, the population, economy and environment can be severely influenced. A dam break is a low-probability socially catastrophic incident that needs to be studied. Many scholars have contributed to earth-rock dam-break studies [1–4]. Graham conducted an extensive evaluation of dam breaks. Xiao established an event-tree method on dam failures. This paper introduces several causes and modes of earth-rock dam breaks.

Obviously, dam-break floods will bring serious disasters to downstream people. The consequences can be divided into four categories, including losses of life, economic losses, social impacts and environmental impacts. Of course, from a humanitarian point of view, the economy and environment can be sacrificed to save human lives. This is also the main reason that a lot of research has been done on the loss of life. To analyze the loss of life due to dam breaks, there are so many established methods, such as the B&G method, D&M method, Graham method, etc. [1,5–8]. In these methods [9,10], factors such as P_{AR} (people at risk), S_D (severity degree of flood), W_T (warning time), O_T (occurrence time) and

U_D (understanding of P_{AR} to S_D) were considered to estimate the L_{OL} (loss of life). In addition, many studies have been performed to analyze the economic losses, including studies of the 'water-depth-loss" curve, unit loss model, GIS technology and other methods [11–17].

The above methods on loss of life and economic losses have achieved good results. However, few studies were focused on the social and environmental impacts. With a better understanding of various factors in the loss of life, people can manage to reduce the dam-break loss of life. Additionally, the popularity of electronic accounts and the development of the insurance industry can also transfer the risks of economic losses. However, the significance of the social and environmental impact evaluation has gradually increased consciousness of sustainable and green developments [18].

Several scholars have done some analyses on the social or environmental impacts of dam breaks [19]. He et al. [20] presented multitarget methods and stage division to establish an index system for the social and environmental effect evaluation of dam breaks. Wang et al. [8,21] presented a risk criterion of the social and environmental impacts in China using the F-N curve method. Cheng et al. [22] used the theoretical basis of fuzzy mathematics to analyze and evaluate the environmental impact of dam failures and took the Shaheji Reservoir as the research object. He et al. [23] used the index weights in combination with the analytic hierarchy process (AHP) to establish a variable fuzzy set evaluation model for the dam-breach environmental impact assessment.

At present, evaluation methods are mainly through the construction of the linear weighted evaluation function, which subjectively determines the severity coefficient of each influencing factor. The evaluation results are too simple, which does not provide enough information on the consequences [24]. For the fuzzy comprehensive evaluation method, the membership function is constructed, and the characteristics of each influential factor are considered comprehensively, which makes the evaluation process more reasonable and accurate. Based on the introduction of the traditional linear weighted evaluation function, this paper further discusses the fuzzy comprehensive evaluation method [25] in order to provide a more reasonable reference for reservoir risk decision makers.

It is a complex and difficult problem to evaluate the social and environmental impacts of earth-rock dam breaks since it involves a wide range of contents that are difficult to define or classify and mostly vague. This paper formulates the evaluation index system for earth-rock dam breaks on society and the environment regarding the characteristics of earth-rock dam breaks and the needs of practical operations. Based on the evaluation indices in these two fields, the evaluation criteria are established, and the qualitative evaluation is determined accordingly. The fuzzy comprehensive evaluation method is used to put forward the evaluation model of dam breaks' impact on society and the environment, and the method is applied to the Liujiatai Reservoir. The evaluation process is meticulous and reasonable. The results show that the evaluation grade of the social and environmental impact of the dam break of the Liujiatai Reservoir was "serious", and several suggestions are proposed according to the actual situation. From the analysis results on the Liujiatai Reservoir, similar dams in China should take corresponding measures in advance to reduce the social and environmental impacts of earth-rock dam breaks.

2. Introduction to Earth-Rock Dam Breaks

2.1. Statistics of Earth-Rock Dams

Figure 1, which we made in a previous paper [4], shows the percentages of earth-rock dams, masonry dams, concrete dams and other dams in China and other countries. From Figure 1, earth-rock dams are the majority of all dams, accounting for 70.0% in the world (excluding China) and 93.9% in China.

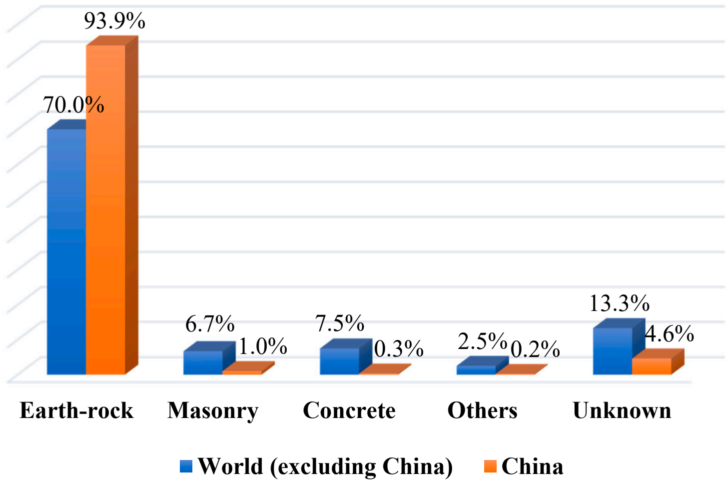

Figure 1. Statistics of dam types in the world (excluding China) and China [4].

In China, there have been several serious earth-rock dam-break events since the 1960s, which are shown in Table 1.

Table 1. Several large dam-break events and deaths in China.

Dam Name	Location	Date	Dam Type	Reservoir Volume (10^6 m^3)	Deaths
Tiefosi	Shangcheng, Henan province	17 May1960	Clay core wall dam	20	898
Liujiatai	Yixian, Hebei province	8 August 1963	Clay core wall dam	40.5	943
Hengjiang	Jiexi, Guangdong province	15 September 1970	Homogeneous earth dam	78.8	941
Hutai	Fushun, Liaoning province	31 July 1971	Clay core wall dam	3.1	512
Banqiao	Luoyang, Henan province	8 August 1975	Clay core wall dam	492.0	19,701
Shimantan	Wugang, Henan province	8 August 1975	Homogeneous earth dam	91.8	2517

Since earth-rock dams account for such a large proportion of existing dams, and the occurred dam-break events have brought such painful costs, analysis of their breaks is of great importance for disaster prevention and mitigation.

2.2. *Causes and Modes of Earth-Rock Dam Breaks*

According to the earth-rock dam-break mechanisms, the causes can be divided into several types [4,26]: lack of flood control capacity, insufficient structural stability, seepage damage and other conditions. The main break modes are as follows [27,28]: overtopping, dam foundation failure, slope instability, spillway failure and internal erosion. These main break modes were introduced in our previous paper [4], as shown in Figure 2.

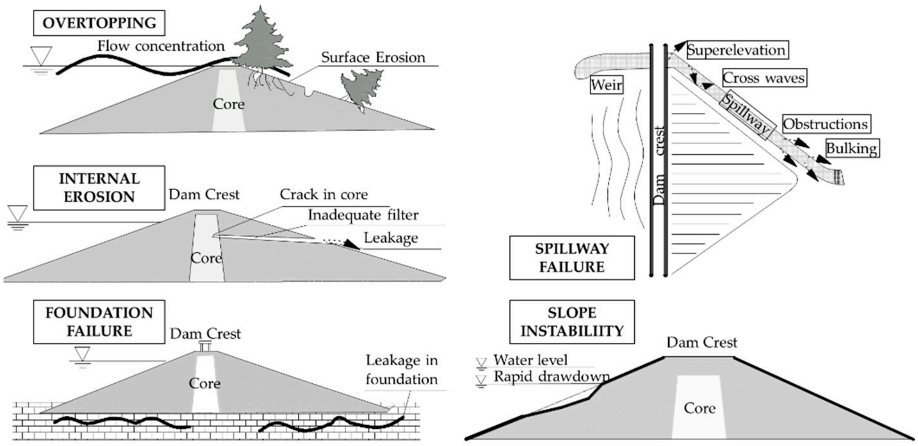

Figure 2. Main modes of earth-rock dam breaks [4].

Among the modes above, the most common one is overtopping [3,29,30], which accounts for 47.8% of dam-break modes in China. It is important to strengthen flood forecasts and take measures in time.

3. Evaluation Principles of Social and Environmental Impacts of Earth-Rock Dam Breaks

Given the good understanding of the loss of life and economic losses due to earth-rock dam breaks, this paper chooses to evaluate the social and environmental impacts resulting from these dam breaks.

Considering the research of other scholars and several rules in China, such as the "General rules for reservoir project management (SLJ 702-80)", "Guidelines on dam safety evaluation (SL258-2000)" and "Technical code for simulation of dam-break flow (SL/T 164-2019)", the following principles should be followed when establishing an evaluation index system:

(1) Principle of simplicity

The conciseness of the index should be considered when selecting the evaluation index for the social impact of earth-rock dam breaks. In other words, the evaluation index should be simple and clear. The required simplicity aims to reduce information redundancy and disorder so as to grasp the main contradiction, avoid confusion, reduce the workload and facilitate the calculation and analysis.

(2) Principle of relevance

The relevance of the evaluation index is to ensure that the evaluation indices have a certain connection so that the index system can form an organic whole.

(3) Principle of relative independence

Each evaluation index should reflect its specific attributes, and compatibility among indices should be excluded as much as possible.

(4) Principle of practicality

The establishment of the evaluation index system needs to be applied in reality, so it is necessary to adhere to the principle of practicality. The indices should have strong accessibility and operability.

(5) Principle of hierarchy

A complete index system should contain different levels, which can be used to reflect the internal structure and key problems of the project index system. The corresponding measures should be facilitated to solve the problems and carry out vertical analysis in addition to horizontal comparison.

(6) Principle of combination of qualitative and quantitative indices

There are two kinds of evaluation indices: one is the quantitative index, and the other is the qualitative index. Qualitative indices are often unable or difficult to be quantified. Qualitative indices can only be evaluated through experts' judgment or quantitative evaluation based on experts' judgment results. These kinds of indices are always indispensable, so the quantitative index and the qualitative index need to be considered as a whole to achieve scientific evaluations and credible results.

3.1. Social Impact Evaluation of Earth-Rock Dam Breaks

The social impact evaluation of earth-rock dam breaks is intended to analyze the impact of a dam break on all aspects of society from macro perspectives. This evaluation mainly includes the loss of life; the political impact, that is, the adverse impact on the stability of the country and society; the decline in daily living standards and quality of life; and the loss of irreparable cultural relics, art treasures and rare animals and plants.

The impact earth-rock dam breaks have on society involves a wide range and multiple aspects. When evaluating the social impact of earth-rock dam breaks, it will be quite difficult to fully consider all aspects of the impact at a time. Meanwhile, it is difficult to determine the evaluation indicators. Currently, there are no relevant research results available. Generally speaking, evaluation indices should be objective, operable, universal and comparable.

According to the above principles [21], the evaluation index system for the social impact of earth-rock dam breaks is established, as shown in Figure 3.

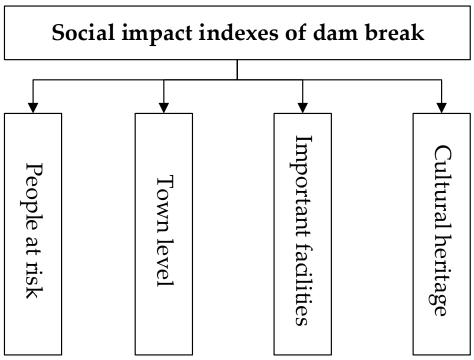

Figure 3. Index system of the social impact of dam breaks.

(1) People at risk

"People at risk" refers to the people affected by the earth-rock dam break. Generally, the more people at risk, the greater the loss of life caused by an earth-rock dam break and the more serious the social impact will be. From the simulation of dam-break floods, the flooded area can be determined, and the people at risk in the flooded area can be investigated.

(2) Town level

Cities and towns are the political, economic, cultural and financial centers in a certain area, so the town level plays an important role in the development and stability of the region. Here, the towns in the dam-break inundation area are divided into seven levels: capital, provincial capital, city, county, town, village and scattered families.

(3) Important facilities

Important facilities are also important contents of social concern. These important facilities include transportation, power transmission, oil and gas trunk lines, factories, mines, enterprises and military facilities, etc. The destruction of these important facilities will affect people's production, their lives and operations of the national economy to a certain extent. The more important these facilities are, the more serious their social impact will be.

(4) Cultural heritage

Cultural heritage includes cultural relics, art treasures and rare animals and plants. The social attention paid to cultural heritage is high, but the value of cultural heritage is difficult to quantify in money. Once a certain piece of cultural heritage is damaged, it may not be easily made up or recovered.

The influence degree is divided into five levels, namely "slight", "ordinary", "medium", "serious" and "extremely serious". The suggested evaluation criteria of the social impact of dam breaks are shown in Table 2 based on the analysis above and several technical codes in China.

Table 2. Suggested evaluation criteria for the social impact of dam breaks.

	People at Risk	N	Town Level	C	Important Facilities	I	Cultural Heritage	H
Extremely serious	$>10^7$	4.0~5.0	Capital Provincial capital	5.0 4.0	National	2.0	World-class	2.5
Serious	10^5~10^7	2.4~4.0	City County	3.0 2.0	Provincial	1.7	National	2.0
Medium	10^3~10^5	1.6~2.4	Town	1.6	Municipal	1.5	Provincial and municipal	1.5
Ordinary	10~10^3	1.2~1.6	Village	1.3	Generally important	1.2	County-level	1.2
Slight	1~10	1.0~1.2	Scattered families	1.0	General	1.0	General	1.0

3.2. Environmental Impact Evaluation of Earth-Rock Dam Breaks

The "environment" refers to all kinds of natural and artificially transformed natural factors affecting human survival and development, including water, land, atmosphere, forests, grasslands, mineral resources, wild plants, wild animals, aquatic organisms, natural relics, scenic spots, ancient sites of cultural interest, sanatoriums, hot springs, living quarters, nature reserves, etc., all of which can be categorized into the natural environment and social environment.

The "environmental impact" refers to the environmental changes caused by human activities and the resulting effects on human society. The environmental impact evaluation of earth-rock dam breaks is intended to evaluate the environmental changes to the downstream inundation area caused by the dam-break flood and the corresponding impact on human society. The environmental impact evaluation of a dam break is a special and specific evaluation that relates to the general environmental impact evaluation but also has its unique characteristics. Therefore, establishing a specific method for the environmental impact evaluation is necessary.

Based on the principles introduced above, the environmental impacts of earth-rock dam breaks can be mainly divided into four types: river morphology changes, biological habitat loss, human landscape damage and pollution industries. The evaluation index system of earth-rock dam breaks regarding the environmental impact is also established [21], as shown in Figure 4.

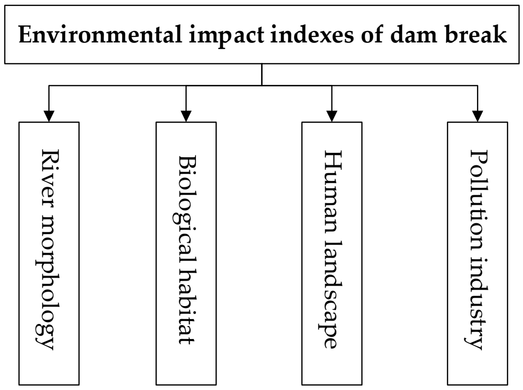

Figure 4. Index system of the environmental impact of dam breaks.

(1) River morphology

Dam-break floods generally spread along the downstream river course. Since the flow velocity of the dam-break flood near the dam site is relatively high and the resulting impact force is strong, the river morphology can be changed easily. Once the river morphology is damaged, the original environment and ecological balance will be broken, which will have a great environmental impact.

(2) Biological habitat

Rivers, forests, wetlands, topsoil and vegetation are places where animals and plants grow, live and reproduce. In order to protect precious animals and plants, the nation has established many nature reserves. Earth-rock dam-break floods will destroy these biological habitats in the downstream flooded area, and the animals and plants that grow and breed in this area will also be seriously influenced.

(3) Human landscape

The human landscape is a kind of landscape composed of cultural characteristics on the basis of natural landscapes in order to fulfill some material and spiritual needs in people's daily lives. The "human landscape" refers to the tourist attractions with certain historical or cultural characteristics and certain physical and spiritual manifestations. This category mainly includes the landscape formed by revolutionary activities, such as modern economic, technological, cultural, artistic and scientific activity places.

(4) Pollution industry

Pollution industries include nuclear facilities, chemical plants, oil refineries, chemical storage facilities, pesticide plants, etc.

According to the principles of conciseness, relativity, relative independence, practicability and hierarchy, the environmental problems of high concern and sensitivity are selected as the environmental impact evaluation indices of earth-rock dam breaks. On this basis, the corresponding criteria of these indices are established and shown in Table 3.

Table 3. Suggested evaluation criteria for the environmental impact of dam breaks.

	River Morphology	R	Biological Habitat Loss	B	Human Landscape Damage	L	Pollution Industry	P
Extremely serious	Big river diversion General river diversion	5.0 4.0	World-class endangered animals and plants	2.0	World-class	2.5	Nuclear power plant or nuclear storage	4.0
Serious	Severe damage to big river Severe damage to general river	3.0 2.0	Rare animals and plants	1.7	National	2.0	Highly toxic chemical plant	2.0
Medium	Certain damage to big river	1.6	Precious animals and plants	1.5	Provincial and municipal	1.5	Large-scale chemical plant	1.6
Ordinary	Certain damage to general river	1.3	Valuable animals and plants	1.2	County-level	1.2	General chemical plant	1.2
Slight	Slight damage to river	1.0	General animals and plants	1.0	Slight damage	1.0	Basically pollution-free industry	1.0

The limit values of each factor in Tables 2 and 3 are divided into 5.0, 4.0, 2.5 and 2.0 according to their contribution to the social and environmental impact index (equivalent to weight). Combined with them, each limit value can be converted into weight. For example, the limit value of 5.0 can be converted to 0.182 with Equation (1).

$$\omega = 5.0/(5.0 + 5.0 + 2.0 + 2.5 + 5.0 + 2.0 + 2.0 + 4.0) = 0.182 \tag{1}$$

For the same reason, the weight coefficients of the social and environmental factors are obtained as shown the Table 4.

Table 4. Limit values and weight coefficients of social and environmental factors.

	Limit Value	Weight Coefficient
People at risk	5.0	0.182
Town level	5.0	0.182
Important facilities	2.0	0.073
Cultural heritage	2.5	0.091
River morphology change	5.0	0.182
Biological habitat loss	2.0	0.073
Human landscape damage	2.0	0.073
Pollution industry	4.0	0.145

4. Fuzzy Comprehensive Evaluation Method

The evaluation method of an earth-rock dam break's impact on society and the environment is related to the reliability of the conclusion. At present, the domestic comprehensive evaluation method mainly adopts the linear weighted evaluation function, which subjectively constructs and determines the severity coefficient of each influencing factor, providing oversimplified evaluation results with insufficient information. For the fuzzy comprehensive evaluation method, the membership function is constructed, and the characteristics of each influencing factor are considered comprehensively, which makes the evaluation process more reasonable and accurate. Based on the introduction of the traditional linear weighted evaluation function, this paper further discusses the fuzzy comprehensive evaluation method to provide a more reasonable basis for reservoir risk decision makers.

4.1. Traditional Linear Weighted Comprehensive Evaluation Function

In reference [21], the evaluation function L of the dam break's impact has been introduced, where the severity coefficient of the evaluation factors of the social and environmental impact is F_3, $F_3 = \frac{1}{4} lg f$ and f is the corresponding impact index.

On the basis of the above method, the evaluation function of the dam break's impact on society and the environment is recorded as L:

$$L = S_1 F_1 + S_2 F_2 \tag{2}$$

where S_1 and S_2 represent the weight of the social and environmental impact index, respectively; F_1 and F_2 represent the social and environmental impact index, respectively.

The influencing factors of the quantitative expression can be treated according to the Table 5.

Table 5. Quantitative expression of qualitative influencing factors.

	Extremely Serious	Serious	Medium	Ordinary	Slight
Severity factor	0.8 ~ 1.0	0.6 ~ 0.8	0.4 ~ 0.6	0.2 ~ 0.4	0 ~ 0.2

The linear weighting function method is simple and easy to operate, but the sensitivity of the method is not high, so the result provides limited information to decision makers, and therefore, the linear weighting function method is only suitable for preliminary evaluation.

4.2. Fuzzy Comprehensive Evaluation Method

Fuzzy comprehensive evaluation is a comprehensive decision made on something for a certain purpose in a fuzzy environment, considering the influence of many factors [31,32].

Suppose that $U = \{u_1, u_2, \cdots, u_n\}$ is a factor set and $V = \{v_1, v_2, \cdots v_n\}$ is an evaluation set. Generally, the influence of various factors on things is inconsistent. Therefore, the weight distribution of factors can be regarded as a fuzzy set on U, which is recorded as A.

$$A = (a_1, a_2, \cdots, a_n) \in F(U) \tag{3}$$

$$\sum_{i=1}^{n} a_i = 1 \tag{4}$$

where a_i represents the weight of the influence factor u_i.

Similarly, B can also be recorded as a fuzzy set on the evaluation set V.

$$B = (b_1, b_2, \cdots, b_m) \in F(V) \tag{5}$$

where b_j represents the $j-$ th decision in the evaluation of the overall V.

Suppose there is a fuzzy relationship $R = \left(r_{ij}\right)_{n\times m}$ between U and V.

Then (U, V, R) constitutes a fuzzy comprehensive evaluation that is like a "converter". When a weight distribution $A = (a_1, a_2, \cdots, a_n) \in F(U)$ is the input, an overall evaluation $B = A \otimes R = (b_1, b_2, \cdots, b_m) \in F(V)$ is the output.

$$B = (b_1, b_2, \cdots, b_m) = A \otimes R = (a_1, a_2, \cdots, a_n) \otimes \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{6}$$

Generally, the symbol of $\otimes$ is used as the max/min calculation. This paper selects the principal factor determinant model.

$$b_j = max\left(a_i \wedge r_{ij}\right), i = 1, 2, \cdots, n, j = 1, 2, \cdots, m \tag{7}$$

In Equation (6), r_{ij} is determined by the membership function that can be chosen as trapezoidal distribution and semitrapezoidal distribution. The evaluation criteria is shown in Table 6.

Table 6. Evaluation criteria of dam-break consequence indices.

Evaluation Index	Extremely Serious	Serious	Ordinary	Medium	Slight
u_i	$> a_{i1}$	$a_{i2} < x \le a_{i1}$	$a_{i3} < x \le a_{i2}$	$a_{i4} \le x \le a_{i3}$	$a_{i5} \le x \le a_{i4}$

According to Table 6, the membership function can be established.

$$
\begin{gathered}
u_{i1}(x) = \begin{cases} 1 & x > a_{i1} \\ \frac{x-a_{i2}}{a_{i1}-a_{i2}} & a_{i2} < x \le a_{i1} \\ 0 & a_{i5} \le x \le a_{i2} \end{cases},\ u_{i2}(x) = \begin{cases} \frac{a_{i1}}{x} & x > a_{i1} \\ 1 & a_{i2} < x \le a_{i1} \\ \frac{x-a_{i3}}{a_{i2}-a_{i3}} & a_{i3} < x \le a_{i2} \\ 0 & a_{i5} \le x \le a_{i3} \end{cases} \\
u_{i3}(x) = \begin{cases} 0 & x > a_{i1} \\ \frac{a_{i1}-x}{a_{i1}-a_{i2}} & a_{i2} < x \le a_{i1} \\ 1 & a_{i3} < x \le a_{i2} \\ \frac{x-a_{i4}}{a_{i3}-a_{i4}} & a_{i4} \le x \le a_{i3} \\ 0 & a_{i5} \le x \le a_{i4} \end{cases},\ u_{i4}(x) = \begin{cases} 0 & x > a_{i2} \\ \frac{a_{i2}-x}{a_{i2}-a_{i3}} & a_{i3} < x \le a_{i2} \\ 1 & a_{i4} < x \le a_{i3} \\ \frac{x-a_{i5}}{a_{i4}-a_{i5}} & a_{i5} \le x \le a_{i4} \end{cases} \\
u_{i5}(x) = \begin{cases} 0 & x > a_{i3} \\ \frac{a_{i3}-x}{a_{i3}-a_{i4}} & a_{i4} < x \le a_{i3} \\ 1 & a_{i5} \le x \le a_{i4} \end{cases}
\end{gathered}
\tag{8}
$$

Based on the calculation above, according to the principle of maximum membership, the evaluation factor v_{j0} is obtained.

$$v_{j0} = max\{b_1, b_2, \cdots, b_m\} \tag{9}$$

The comprehensive evaluation of earth-rock dam-break consequences is a complex evaluation system that needs to consider multiple factors. A lot of information will be lost during the calculation. Therefore, a multilevel fuzzy comprehensive evaluation model is used in this paper.

In the multilevel fuzzy comprehensive evaluation model, the factor set is divided into several categories according to its attributes, and each aspect of the single-factor evaluation is the result of multifactor synthesis at the lower level. Similarly, the output value of the single-factor evaluation at the lower level is smaller.

The steps of the multilevel fuzzy comprehensive evaluation model are shown below.

Step 1: Divide the factor set A into S subsets according to its attributes:

$$U_i = \left\{u_{i1}, u_{i2}, \cdots, u_{in_i}\right\},\ i = 1, 2, \cdots, S \tag{10}$$

The following conditions need to be met:

$$U_1 \cup U_2 \cup \cdots \cup U_S = U; U_i \cap U_j = \varnothing, i \neq j \tag{11}$$

The social and environmental impact evaluation of earth-rock dam breaks can be obtained from the combination of the social impact and environmental impact at a lower level, which means the social impact evaluation can be obtained from the factors of “people at risk”, “town level”, “important facilities” and “cultural heritage”, and the environmental impact can be obtained from the factors of “ecological environment”, “river morphology”, “biological habitat”, “human landscape” and “pollution industry”.

Step 2: Evaluate each subfactor U_i comprehensively. For the evaluation set $V = \{v_1, v_2, \cdots, v_m\}$, the weight distribution of each factor in U_i relative to V is

$$A_i = \left(a_{i1}, a_{i2}, \cdots, a_{in_i}\right) \tag{12}$$

If R_i is a matrix of the single-factor evaluation, the first-level evaluation vector B_i can be obtained by

$$B_i = A_i \otimes R_i = (b_{i1}, b_{i2}, \cdots, b_{im}), i = 1, 2, \cdots, S \tag{13}$$

Step 3: Take each U_i as a factor, and μ is another factor set, where $\mu \triangleq \{U_1, U_2, \cdots, U_S\}$. The matrix of the single-factor evaluation is

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_S \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix} \tag{14}$$

Take each U_i as a part of U, which can reflect some properties of U. The weight distribution can be given according to their importance: $A = (a_1, a_2, \cdots, a_n)$. Then, the second-level evaluation vector can be obtained: $B = A \otimes R = (b_1, b_2, \cdots, b_m)$.

If each subfactor set U_i, $i = 1, 2, \cdots, S$ still has too many factors, it can be divided further, and the third- or fourth-level model can be established.

The fuzzy comprehensive evaluation method realizes the effective combination of qualitative and quantitative analysis with the membership degree and membership function and is convenient for multilevel processing. The evaluation result is a vector with rich information, and it therefore can accurately depict the evaluated objects. The output vector can be further processed to obtain reference information. Moreover, the evaluation is carried out object by object, so there is only an evaluation value for the evaluated objects, which is not influenced by the piling-up of objects. Therefore, the proposed fuzzy comprehensive evaluation method is applicable to evaluating the social and environmental impact of earth-rock dam breaks.

5. Engineering Project

5.1. Project Introduction

Located in the upper reaches of the Boundary River, Baoding city, Hebei province, the Liujiatai Reservoir has a control basin area of 174 km^2. The total storage capacity is 40.5×10^6 m^3, with the corresponding water level of 138.40 m. The reservoir construction was started in February 1958 and basically completed in July 1959. The reservoir dam is a clay core earth dam with a length of 295 m, crest elevation of 138.80 m, maximum dam height of 35.8 m, crest width of 5 m and wave wall height of 1.0 m.

From 2 August 1963 to 8 August 1963, the largest rainstorm occurred in the Boundary River Basin since the start of records in mainland China. The average rainfall in the whole basin was 898 mm, among which the maximum rainfall on 7 August was 448.5 mm, which was rare in China. Due to the low flood control standard and poor engineering quality, the dam overtopped and burst at 3:55 a.m. on 8 August. The bottom width of the gap at the right end of the dam was 80 m, and the upper opening was 155 m. Figure 5 shows the location and flooded area of the Liujiatai Reservoir.

Figure 5. Location and flooded area of the Liujiatai Reservoir.

In Yi County, where the reservoir is located, there are six national key cultural relics protection units and eight provincial key cultural relics protection units of world cultural heritage: the Western Tomb of the Qing Dynasty. According to the survey, the number of P_{AR} was 64,941. The dam break caused a certain degree of water and soil loss and farmland damage in the lower reaches, resulting in water pollution and a certain degree of damage to the river morphology. In the flooded area, there were some small pollution enterprises, such as small chemical plants and pesticide plants, and no rare animals or plants.

Combined with the actual situation of the Liujiatai Reservoir and the evaluation criteria in Table 7, the measurement scores of various factors of the social and environmental impact of the dam break were obtained.

Table 7. Actual situation and scores of the evaluation index system.

	Weight Coefficient	Actual Situation	Score
People at risk	0.182	64,941	2.5
Town level	0.182	City	3.0
Important facilities	0.073	National	1.9
Cultural heritage	0.091	World-class	2.3
River morphology	0.182	Certain damage to big river	2.1
Biological habitat loss	0.073	Valuable animals and plants	1.4
Human landscape damage	0.073	Provincial and municipal	1.6
Pollution industry	0.145	General chemical plant	1.1

5.2. Application of the Traditional Linear Weighted Comprehensive Evaluation Function

According to Table 7, using linear interpolation, the severity coefficients of each evaluation index were obtained, as shown in Table 8.

Table 8. Severity coefficients of each evaluation index.

	Weight Coefficient	Severity Coefficient
People at risk	0.182	0.613
Town level	0.182	0.667
Important facilities	0.073	0.733
Cultural heritage	0.091	0.720
River morphology change	0.182	0.607
Biological habitat loss	0.073	0.333
Human landscape damage	0.073	0.500
Pollution industry	0.145	0.100

Then, for the evaluation of the social and environmental impact of the dam break, the linear weighted synthesis function is

$$F = \sum_{i=1}^{8} S_i f_i = 0.538 \in [0.4 \sim 0.6] \tag{15}$$

The results show that the social and environmental impact assessment level was medium, with a serious bias.

5.3. Application of the Fuzzy Comprehensive Evaluation Method

According to the definition of the membership function, we can get the single-factor evaluation matrix $R = (r_{ij})_{n\times m}$ to carry out a multilevel fuzzy comprehensive evaluation.

Step 1: The evaluation factors of the social and environmental impact can be divided into two parts—social impact factors and environmental impact factors.

$$U_i = \{u_{i1}, u_{i2}\} \tag{16}$$

where the social impact evaluation can be obtained by the factors of "people at risk", "town level", "important facilities" and "cultural heritage", while the environmental impact can be obtained by the factors of "ecological environment", "river morphology", "biological habitat", "human landscape" and "pollution industry".

Step 2: Evaluate each subfactor U_i comprehensively. For the evaluation set $V = \{v_1, v_2, \cdots, v_m\}$, the weight distribution of each factor in U_i relative to V is

$$\begin{gathered} A_i = \left(a_{i1}, a_{i2}, \cdots, a_{in_i}\right) \\ A_1 = [0.345\ 0.345\ 0.138\ 0.172] \end{gathered} \tag{17}$$

$$A_2 = [0.385\ 0.154\ 0.154\ 0.308] \tag{18}$$

If R_i is a matrix of the single-factor evaluation, the first-level evaluation vector B_i can be obtained by

$$B_i = A_i \otimes R_i = (b_{i1}, b_{i2}, \cdots, b_{im}) \tag{19}$$

$$\begin{gathered} B_1 = A_1 \otimes R_1 = [0.345\ 0.345\ 0.138\ 0.172] \otimes \begin{bmatrix} 0.063 & 1 & 0.937 & 0 & 0 \\ 0.5 & 1 & 0.5 & 0 & 0 \\ 0.667 & 1 & 0.333 & 0 & 0 \\ 0.6 & 0 & 0.4 & 0 & 0 \end{bmatrix} \\ = [0.172\ 0.345\ 0.323\ 0\ 0] \\ B_2 = A_2 \otimes R_2 = [0.384\ 0.154\ 0.154\ 0.308] \otimes \begin{bmatrix} 0.05 & 1 & 0.95 & 0 & 0 \\ 0 & 0 & 0.667 & 1 & 0.333 \\ 0 & 0.8 & 1 & 0.2 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \end{bmatrix} \\ = [0\ 0.384\ 0.365\ 0.192\ 0.154] \end{gathered} \tag{20}$$

Step 3: The first-level evaluation of the overall impact is

$$\begin{gathered} B = A \otimes R = [0.527\ 0.473] \begin{bmatrix} 0.172 & 0.345 & 0.323 & 0 & 0 \\ 0 & 0.384 & 0.365 & 0.192 & 0.154 \end{bmatrix} \\ = [0.091\ 0.182\ 0.172\ 0.091\ 0.146] \end{gathered} \tag{21}$$

According to the principle of maximum membership, the proportion of "serious" in the social and environmental impact evaluation of the Liujiatai Reservoir dam break was the largest. Additionally, the proportion of "medium" was also relatively large. Therefore, the evaluation result of the comprehensive social and environmental impact of the dam break in the Liujiatai Reservoir was "serious" and tended to be "moderate". The result is similar to but a little more serious than that calculated by the traditional linear weighted comprehensive evaluation function.

In view of the social and environmental impact index system and evaluation results, protective measures should be taken in advance, such as transfer exercises for the at-risk population, the waterproof treatment of important facilities and cultural heritage sites, the treatment of river erosion and protection of pollution sources from polluting enterprises.

6. Conclusions

Since earth-rock dams occupy a large proportion of dams, it is necessary to analyze the causes and the modes of earth-rock dam breaks. In addition to the serious loss of life and economic losses, earth-rock dam breaks will also have a significant impact on the downstream society and environment. The main contents of this paper were as follows:

(1) In combination with the earth-rock dam-break causes and modes, measures should be taken in time, such as strengthening flood level monitoring to prevent overtopping, strengthening the dam to prevent seepage failure, strengthening monitoring to discover the hidden danger in time to prevent internal erosion and so on.
(2) According to the characteristics of earth-rock dam breaks' impact on society and the environment and the needs of practical operations, the social and environmental impact evaluation index system for earth-rock dam breaks was established. The suggested evaluation criteria can be obtained further based on the evaluation indices.
(3) Based on the traditional linear weighting function and the fuzzy comprehensive evaluation method, the social and environmental impact evaluation models of earth-rock dam breaks were separately established. The linear weighted function method was relatively simple in general, easy to grasp and suitable for preliminary assessment. These two methods were applied to the earth-rock dam-break event of the Liujiatai Reservoir. The results show that the evaluation grade of the social and environmental impact of the dam break of the Liujiatai Reservoir was "serious". The fuzzy comprehensive evaluation method was more meticulous and effective.
(4) The method of dam fuzzy comprehensive evaluation can be applied to similar dams. In view of the social and environmental impact, combined with the actual situation of the dam, targeted protective measures should be taken in advance, such as transfer exercises for the at-risk population, the waterproof treatment of important facilities and cultural heritage sites, the treatment of river erosion, the transfer of rare animals and protection of pollution sources from polluting enterprises.

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