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Study on Risk Assessment and Early Warning of Flood-Affected Areas when a Dam Break Occurs in a Mountain River

Qiang Fan, Zhong Tian * and Wei Wang *

State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China; scufanqiang@hotmail.com

* Correspondence: tianzhong@scu.edu.cn (Z.T.); profwang@sina.com (W.W.); Tel.: +86-028-8540-5706 (Z.T.)

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Abstract: Under the influence of extreme weather conditions or other unfavorable factors, if a dam break occurs in a mountain river, it will cause a great number of casualties and property losses in the affected downstream areas. Usually, early warning of the affected areas downstream of the dam depends mainly on qualitative evaluation and cannot be quantitatively evaluated. Based on the authors' calculation of floods for many years, this study presents a quantitative assessment method for flood risk. The Ertan Hydropower Station in Southwest China and the flood-affected areas were chosen as the object of this study. Based on field surveys, research literature data, and the authors' calculations, the basic data of the Ertan Hydropower Station and the calculation results of the dam break were obtained, and 35 representative flood-affected areas were selected to study risk assessment and early warning. The fuzzy analytic hierarchy process (FAHP) was used to build a mathematical model for quantitative analysis. The population, flood arrival time, flood level, evacuation time, and local GDP (Gross Domestic Product) were selected as five typical evaluation factors. Finally, this study calculated and counted the risk level of 35 representative flood-affected areas, and the study results were applied to Quxue and Guanmaozhou Hydropower Station.

Keywords: flood risk; risk assessment and early warning; quantitative assessment; fuzzy analytic hierarchy process; risk level

1. Introduction

The history of the human use of hydropower resources goes back to ancient times. To obtain long-term and stable water energy, dams need to be built in rivers. China is the most populous country in the world, and the huge population pressure has a great demand for electric energy. Due to the needs of economic and social development, many hydropower stations have been built in Southwest China. Meanwhile, the construction of hydropower stations is often accompanied by the appearance of large reservoirs and dams [1,2]. Humans have had a habit of living near rivers since ancient times, which has resulted in large population settlements in the downstream areas of the reservoir [3]. The phenomenon of the co-existence of such reservoirs with humans can be seen everywhere in Southwest China.

There is plenty of rainfall in Southwest China. Furthermore, extreme rainfall has become more frequent, attributed to abnormal climate conditions in recent years. When a catastrophic rainstorm occurs in the flood season, the process of runoff yield and flow concentration in mountain rivers is extremely fast, which makes it easy to form extreme floods. Meanwhile, Southwest China is also one of the regions where geological hazards occur frequently, which is characterized by intense tectonic movement and frequent earthquake activities [4]. In addition, the factors that affect dam safety include hidden engineering quality dangers, geological hazards, mountain collapse, terrorist attacks, war, etc.

When a dam break occurs, the most effective way of cutting down casualties and property losses is to organize rescue forces with all possible resources in accordance with the pre-designed early warning plan. Furthermore, areas with more severe disasters should be given priority rescue [5–9]. Therefore, the risk level of the flood-affected area must be calculated in advance.

Many experts and scholars have carried out a lot of explorations and studies on risk assessment and early warning. For example, Anila C. George used BOSS DAMBRK to analyze the dam break of Thenmala Dam of Kerala State in India [10]; Raffaele Albano et al. studied improving flood risk analysis to effectively support the implementation of flood risk management plans and how to make a reasonable flood risk map to manage the flood risk [11]; Jan Cools et al. studied flood early warning systems, and mainly took an overview of policy formulation on flood management [12]; JH Jang proposed an advanced method to apply multiple rainfall thresholds for urban flood warnings [13,14]; Parker, D.J. studied the European flood warning system [15]; Zheng, X. et al. studied the risk assessment of the tailings dam break [16]; Sifan A. Koriche and Tom H.M. Rientjes used satellite remote sensing technology and a hydrological model for flood early warning, which is a good method to track the process of flood formation in the plain region [17]; C. Delenne. et al. studied uncertainty analysis of river flooding and dam failure risks using local sensitivity computations [18]; M.A.C. Celis et al. calculated the dam-break process by numerical simulation [19]; Abdalla et al. proposed a GIS-supported fuzzy-set approach for flood risk assessment [20]; Hongbo Ma et al. studied a real time prediction approach for floods caused by failure of natural dams due to overtopping [21]; Becker et al. studied flood disaster management in central Europe [22]; and other scholars have also conducted a series of related researches [23–27].

As flood is affected by many factors from generation to disappearance, it is difficult to carry out accurate quantitative calculations in flood-related research [5,28,29]. Previous studies on flood have mainly focused on the stage of qualitative calculation, and few have focused on quantitative calculation. Through the study of relevant literatures and actual calculations, the author found that the fuzzy analytic hierarchy process (FAHP) can be used to solve the problem of risk assessment and early warning in the flood-affected area, and no scholar has used the method of combining FAHP with dam-break flood calculations to conduct a quantitative analysis of a flood-affected area [30–35]. In this study, based on the basic principle of FAHP, the dam-break flood calculation results and the data collected in local fields, the author used Ertan Hydropower Station as an example, assuming that the Ertan Dam was completely broken under the most unfavorable extreme conditions, then the risk level of the 35 flood-affected areas downstream of the dam was calculated.

2. Study Area

2.1. Dam and Reservoir

The Ertan Hydropower Station is in the Southwest of Sichuan Province, downstream of the Yalong River, 46 km away from Panzhihua city, and it is the largest hydropower station built and put into production in China in the 20th century. The dam is a concrete hyperbolic arch dam with the largest height at 240 m and a crest arc length of 774.69 m. The total installed capacity of the power station is 3300 MW, with an average annual electric output of 17 billion kilowatt hours. The Ertan Hydropower Station has a total reservoir capacity of 5.8 billion cubic meters, a reservoir surface of 101 square kilometers, and an annual average runoff of 1670 m^3/s at the dam site. The normal water level is 1200.00 m, the dead water level is 1155.00 m, and the corresponding storage capacity is 5.8 billion cubic meters and 2.43 billion cubic meters, respectively [36].

2.2. Disasters in Previous Years

On 8 June 1967, an incident occurred in the Yalong River where part of the mountains collapsed and blocked the river. The volume of the falling accumulation was up to 68 million cubic meters, forming a 300-m-high barrier lake with a storage capacity of 680 million cubic meters. Eventually, the barrier lake was washed out by the increasing water and led to a maximum dam-break flow of 57,000 m^3/s, and the terrible flood caused great losses. The impact of the flood was eliminated only after it extended to Chongqing (a city in Southwest China, 1700 km away from the barrier lake).

2.3. Earthquake Situation

The Ertan Hydropower Station is in the Panxi Great Rift Valley and the dam site area is situated on the north–south tectonic belt, which is the largest radial tectonic belt in China with frequent and intense seismic activities [37,38]. Since 1987, there have been 33 earthquakes with a magnitude greater than 4.7 within 100 km from the reservoir and dam, of which six earthquakes had a magnitude greater than 6.0. The possibility of dam break due to earthquake is very high in this region.

2.4. Evaluation of Dam-Break Flood

According to the author's previous dam-break flood calculation results (Supplementary Material) and investigation data, the most dangerous situation of dam break should be selected when risk assessment and early warning is carried out on the flood-affected areas. That is to say, the condition of dam break is that the water level of the reservoir has reached the crest elevation and the Ertan Hydropower Station arch dam all burst instantly. At this time, the maximum flood peak flow at the dam site is 457,000 m^3/s, which is more than 19 times that of the check flood flow of 23,900 m^3/s. After 1.67 h, the flood peak moved from the Yalong River to Panzhihua city, with a flood level of 138.00 m (the flood level, which refers to the flood elevation calculated from the zero elevation of the Yellow Sea datum in China, is different from the flood depth). After 4.74 h, the flood peak reached Jiangbian town, with a flood level of 106 m. After 9.94 h, the flood peak reached Tuobuka town, with a flood level of 74.5 m. From the dam site of Ertan Hydropower Station to Tuobuka town, the main affected areas where the dam-break flood flowed through and the corresponding flood levels are shown in Figures 1 and 2.

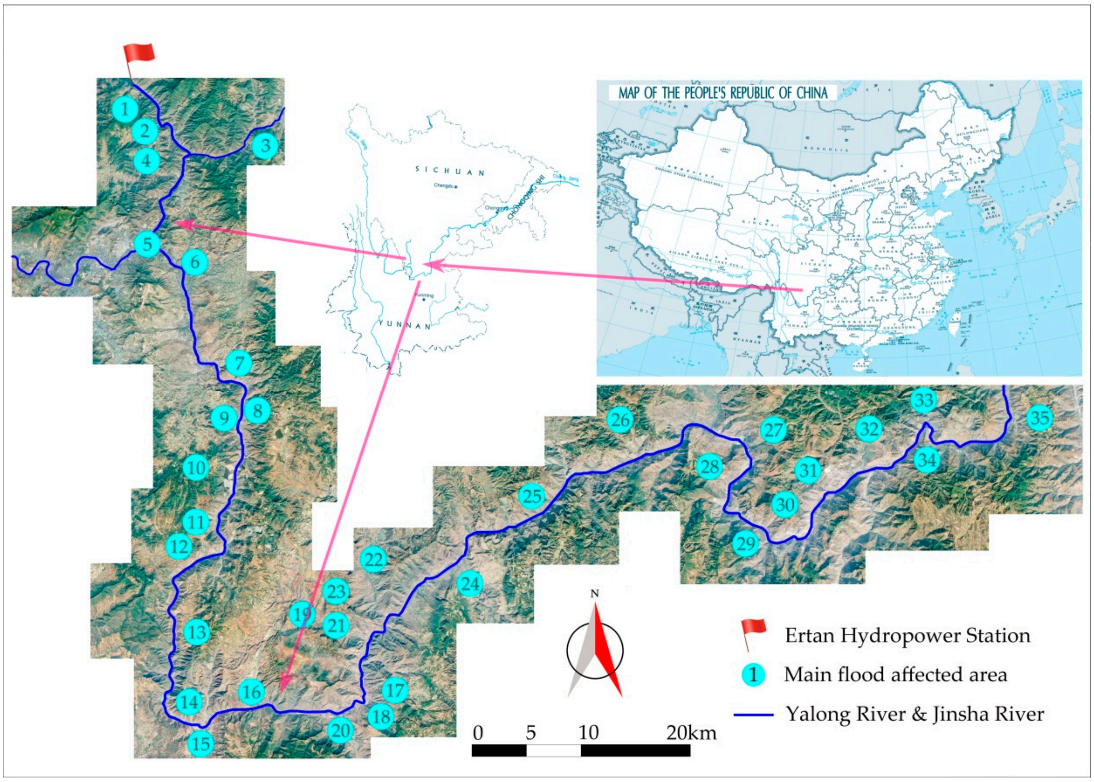

Figure 1. Main flood-affected areas.

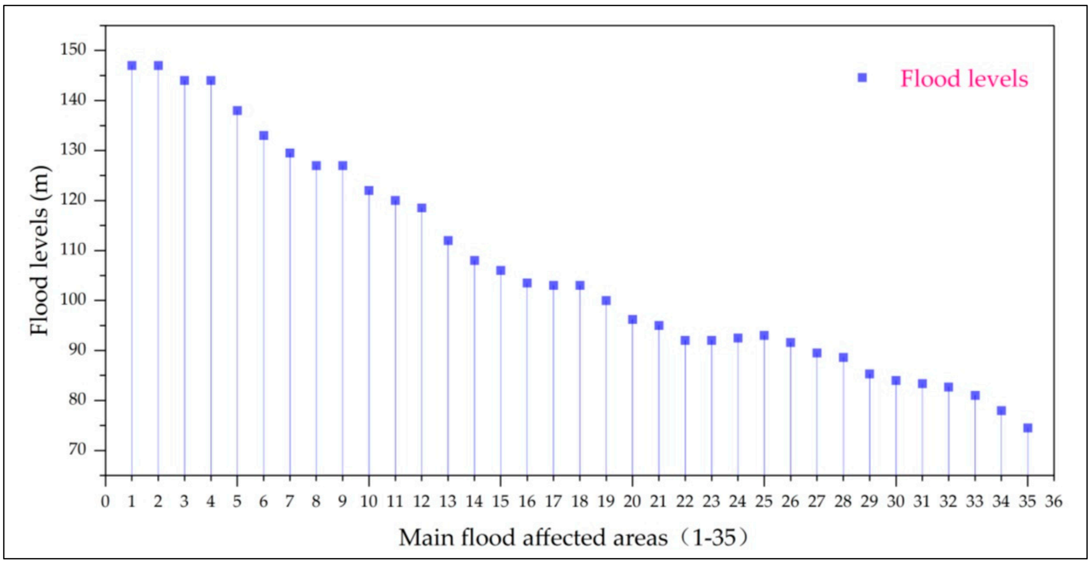

Figure 2. Flood levels of the main affected areas.

To avoid a large number of casualties and property losses caused by dam-break flood, flood early warnings should be issued in advance when a dam break may occur, and disaster victims should be organized to evacuate and seek refuge in the first instance. Due to the different degrees of flood impacts and damages in different regions, it is very important to carry out scientific and rigorous risk assessment and early warning of the flood-affected areas.

2.5. Flood Risk and Its Components

Flood risk takes into account the harm that a flood actually causes. It is a combination of the probability of an event happening and the consequences (impact) if it were to occur. Flooding originates from a variety of sources, of which the dam break is the most common one. A dam is a barrier across flowing water that obstructs, directs, or slows down the flow, often creating a reservoir. Dams are considered "Installations containing dangerous forces" under International humanitarian law due to the massive impact of a possible destruction on the civilian population and the environment. Dam failures are comparatively rare but can cause immense damage and loss of life when they occur.

The main causes of dam failure are as follows: (1) extreme floods: extreme floods are often caused by extremely heavy rainstorms, the scouring of rainstorms and the driving effect of wind and waves in reservoirs can easily cause dam breaks; (2) earthquakes: dams under the action of earthquakes and seismic water pressure are easy to burst; (3) dam quality defect; (4) lack of maintenance; (5) ill operation and management; (6) man-made destruction (wars or terrorist activities); etc.

The dam break entails huge flood risk. The flood risk includes the following: (1) many casualties; (2) houses will be destroyed; (3) farmland will be submerged; roads, bridges, communications-equipment and transmission lines will be destroyed; (4) water sources will be polluted; (5) shortage of food and necessities; (6) secondary disasters; etc.

According to the design report of Ertan Hydropower Station, apart from the destruction of great earthquakes and wars, the dam will not break more than 1/4 of the whole dam in general. When there is a serious earthquake with a seismic intensity more than 8 or a war, the probability of full dam break can reach more than 60%.

3. Methodology

3.1. Fuzzy Analytic Hierarchy Process

The FAHP, which is a comprehensive analysis method combining the analytic hierarchy process (AHP) and fuzzy synthetic evaluation method (FSEM), was proposed by Professor T.L. Saaty of American operation research in the 1970s [39,40]. FAHP is used to solve the quantization problems of the evaluation factors with unclear boundaries and difficult quantifications. The basic idea is to decompose the problem itself hierarchically according to the nature of the multi-objective evaluation problem and the general objective and form a bottom-up step hierarchical structure.

AHP is one of the most widely used subjective weighting methods at present. This method can make use of less quantitative information to carry out scientific quantitative analysis of the problems, which are difficult to measure directly and accurately [41–44]. The idea of solving the problem contains the following basic steps: establish the hierarchical structure model, construct the judgment matrix, calculate the single ordering weight value, and check the consistency, calculate the total sequencing weight value and check the consistency, and finally, calculate the combined weight of the elements of each level to the total objective. The disadvantage of AHP is that it has a strong subjectivity, and there is a problem that the consistency of human judgment and the consistency of the judgment matrix are different. The FSEM is a comprehensive evaluation method based on fuzzy mathematics. This method takes the influence of multiple factors into account under the fuzzy environment, using the principle of fuzzy transform and the maximum membership to make a general evaluation of things or objects. FSEM has the characteristics of clear results and being strong systematic. This method overcome the shortcoming of AHP in single factor evaluation [45,46].

3.2. Combination of FAHP and Analysis of Mountain Rivers

Due to the influence of climate change and population migration in the mountain areas, factors such as meteorology, hydrology, geography, social activity, and industry in the study area are fuzzy and difficult to quantify. Based on FAHP, the relative mathematical model was established by the author to study the risk assessment and early warning of the flood-affected area when a dam break occurs in a mountain river.

4. Application of FAHP

To use FAHP to solve problems, a comprehensive evaluation index system should be first established. According to the theory of fuzzy mathematics, the fuzzy decision of a multi-objective system can be represented by $\mathbf{B} = \mathbf{W} \bullet \mathbf{R}$ ("$\bullet$" refers to fuzzy transformation), where $\mathbf{W}$ represents the weight vector of typical evaluation factors in the comprehensive evaluation index system, $\mathbf{R}$ represents the judgment matrix of a single factor determined by the principle of maximum membership degree, and $\mathbf{B}$ represents the fuzzy comprehensive evaluation set. Therefore, the key to carry out the risk assessment and early warning of the affected areas accurately is to determine the weight vector $\mathbf{W}$ and judgment matrix $\mathbf{R}$.

Assume that n factors composed the factor set $\mathbf{A}$, $\mathbf{A} = (a_1, a_2, a_3 \ldots a_n)$, m evaluation results composed the evaluation set $\mathbf{V}$, $\mathbf{V} = (v_1, v_2, v_3 \ldots v_m)$, the weight values of n factors composed of the weight vector $\mathbf{W}$, $\mathbf{W} = (w_1{}', w_2{}', w_3{}' \ldots w_n{}')$, $w_i{}'$ is the weight value of the factor a_i and $\sum\limits_{i=1}^{n} w_i' = 1$. The single factor fuzzy evaluation set $\mathbf{R}_i$ of a_i is the fuzzy subset of evaluation set $\mathbf{V}$; let $\mathbf{R}_i = (r_{i1}, r_{i2}, r_{i3} \ldots r_{in})$, so the judgment matrix $\mathbf{R}$ can be expressed as:

$$\mathbf{R} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & \cdots & r_{1n} \\ r_{21} & r_{22} & r_{23} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{i1} & r_{i2} & r_{i3} & \cdots & r_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & r_{n3} & \cdots & r_{nn} \end{pmatrix}$$

The fuzzy comprehensive evaluation set can be represented by **B** = **W**•**R** ("•" refers to fuzzy transformation), the jth vector b_j of set **B** is the jth degree of risk membership, according to the maximum element value in the vector b_j, the risk level of the flood-affected areas can be obtained. To make the calculation accurate and reasonable, the fuzzy transformation "•" in this study used the M (•,⊕) model, that is: $a \bullet b = a \times b$, $a \oplus b = \min(1, a + b)$. In this study, there are five evaluation factors and five types of risk assessment, so $n = 5$, $m = 5$.

4.1. Establish Hierarchical Structure Model

After a dam break occurs, the risk assessment and early warning of the flood-affected area are closely related to five typical evaluation factors: the population, flood arrival time, flood level, evacuation time, and local GDP. By using the principle of AHP, the comprehensive evaluation index system for flood-affected areas can be established, as shown in Figure 3. After establishing the comprehensive evaluation index system, the AHP can be used to determine the weight of the typical evaluation factors.

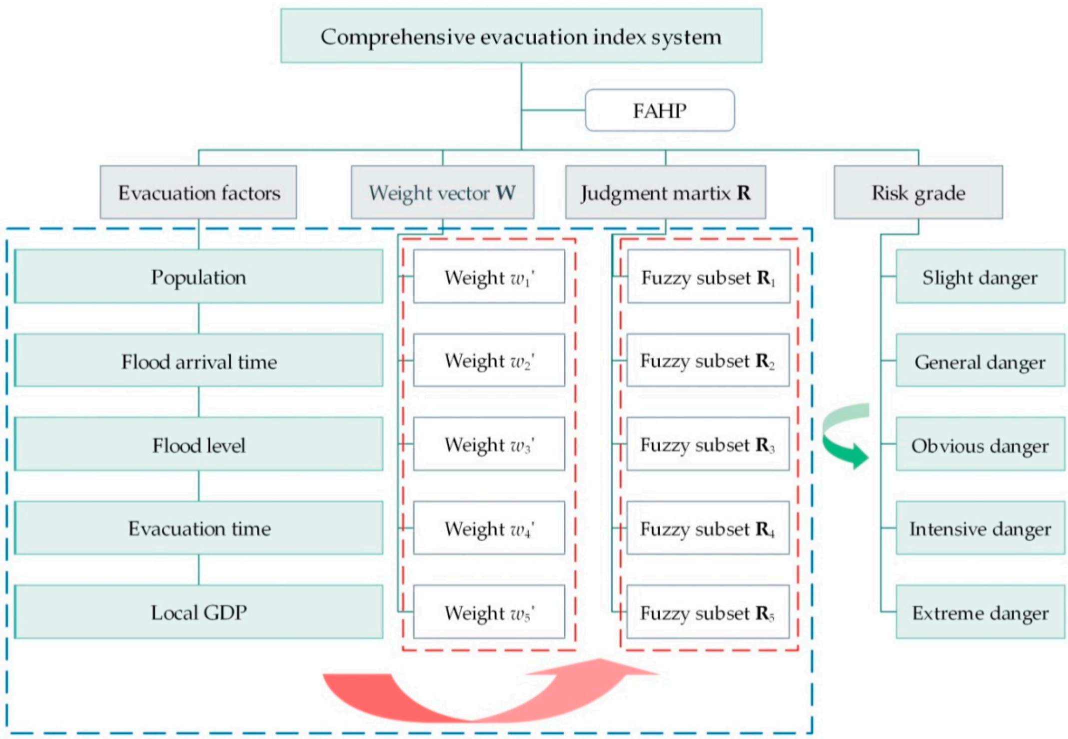

Figure 3. The comprehensive evaluation index system for the flood-affected areas.

4.2. Use AHP to Determine the Weight Vector **W**

4.2.1. Construct Judgment Matrix

The core of AHP is to construct a judgment matrix among the various factors by using the scale method of "1–9", that is, using integers among "1–9" and its reciprocal as scale values to indicate the importance of pairwise comparison among the evaluation factors. The digital scale value and the significance of the "1–9" scale method are shown in Table 1 [46,47].

Table 1. Numeric scale and its significance.

Digital Scale Value	The Significance
1	Two elements comparison, with the same importance
3	Two elements comparison, the element i is slightly more important than the element j
5	Two elements comparison, the element i is obviously more important than the element j
7	Two elements comparison, the element i is intensively more important than the element j
9	Two elements comparison, the element i is extremely more important than the element j
2, 4, 6, 8	Take the average value of the adjacent judgment value
Reciprocal	If the importance ratio of element i to element j is a_{ij}, the importance ratio of element j to element i is $a_{ji} = 1/a_{ij}$

According to the in-depth research and investigation of the study area, the author contrasted Table 1 to determine the digital scale values of the evaluation factors, an n-order reciprocal matrix $\mathbf{A}^* = (a_{ij})_{n\times n}$, was obtained, and $\mathbf{A}^*$ can be expressed as:

$$\mathbf{A}^* = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & a_{ij} & \cdots \\ a_{n1} & \cdots & \cdots & a_{nn} \end{pmatrix}$$

where $a_{ij} \times a_{ji} = 1$, $a_{ii} = a_{jj} = 1$.

4.2.2. Calculate the Single Ordering Weight Value and Check the Consistency

Since the judgment matrix is given artificially with certain subjectivity, the judgment matrix established in the actual work often does not have complete consistency, so it is necessary to check the consistency of the matrix to evaluate the reliability. Calculating the single ordering weight value refers to the importance weight calculation of the lower level factors relative to the upper level factors based on the judgment matrix, which is the basis of the importance ranking of all factors in the index level relative to the target level. For the judgment matrix $\mathbf{A}^*$, there is the $\mathbf{A}^* \bullet \mathbf{W} = \lambda_{\max} \bullet \mathbf{W}$ ("$\bullet$": matrix product symbol, here refers to dot product), where, $\lambda_{\max}$ is the largest eigenvalue of the judgment matrix $\mathbf{A}^*$, $\mathbf{W}$ is the n-order normalized eigenvector of the judgment matrix $\mathbf{A}^*$, and the component W_i' of $\mathbf{W}$ is the single ordering weight value of the corresponding factor. The root mean square method (RMS) can be used to calculate the n-order normalized eigenvector $\mathbf{W}$ and the largest eigenvalue $\lambda_{\max}$, and a random consistency index table can be used to check the consistency. The calculation process is as follows:

First, calculate the product M_i of each row of elements and the n-th root W_i of M_i:

$$M_i = \prod_{j=1}^{n} a_{ij}; i = 1, 2, 3, \cdots, n \quad (1)$$

$$W_i = \sqrt[n]{M_i}; i = 1, 2, 3, \cdots, n \tag{2}$$

Then, calculate the largest eigenvalue $\lambda_{\max}$ of the judgment matrix **A***:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{a_{i1}W_1 + a_{i2}W_2 + \cdots + a_{in}W_n}{nW_i}; i = 1, 2, 3 \cdots, n \tag{3}$$

To make the judgment results consistent with the actual situation, the consistency check of the judgment matrix **A*** must be performed. The check index is CR (consistency ratio), CR = CI/RI, where CI is the consistency index and CI = $(\lambda_{\max} - n)/(n - 1)$, RI is the random consistency index and the value of RI can be looked up from Table 2.

Table 2. Random consistency index.

Matrix Order (n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54	1.56	1.58	1.59

When CR = 0, the judgment matrix **A*** has complete consistency; when CR $\leq$ 0.1, the judgment matrix **A*** has a relatively satisfactory consistency; the greater the value of CR, the worse the consistency of A*. Therefore, when CR $\leq$ 0.1, the calculation process can be continued, when CR > 0.1, the judgment matrix **A*** needs to be corrected and recalculated.

Finally, normalize the eigenvector **W**, the component $W_i^{'}$ of **W** can be calculated:

$$W_i^{'} = W_i / \sum_{i=1}^{n} W_i; i = 1, 2, 3, \cdots, n \tag{4}$$

Therefore, the weight vector **W** = $(w_1^{'}, w_2^{'}, w_3^{'} \ldots w_n^{'})$.

4.2.3. Solve Weight Vector **W**

Five typical evaluation factors are represented by a_1–a_5, the importance of pairwise comparison among the evaluation factors can be determined by Table 1, and the results are shown in Table 3.

Table 3. The importance table of pairwise comparison among evaluation factors.

a_i \ a_j	a_1	a_2	a_3	a_4	a_5
a_1	1	5	3	5	7
a_2	1/5	1	1/3	1	3
a_3	1/3	3	1	3	5
a_4	1/5	1	1/3	1	3
a_5	1/7	1/3	1/5	1/3	1

Use matrix **A*** to represent the result, that is:

$$\mathbf{A}^* = \begin{pmatrix} 1 & 5 & 3 & 5 & 7 \\ \frac{1}{5} & 1 & \frac{1}{3} & 1 & 3 \\ \frac{1}{3} & 3 & 1 & 3 & 5 \\ \frac{1}{5} & 1 & \frac{1}{3} & 1 & 3 \\ \frac{1}{7} & \frac{1}{3} & \frac{1}{5} & \frac{1}{3} & 1 \end{pmatrix}$$

According to Equations (1)–(3):

M_1 = 525, M_2 = 1/5, M_3 = 15, M_4 = 1/5, M_5 = 1/315.
W_1 = 7/2, W_2 = 661/912, W_3 = 55/32, W_4 = 661/912, W_5 = 219/692.
$\lambda_{\max} = \sum_{i=1}^{n} \frac{a_{i1}W_1 + a_{i2}W_2 + \cdots + a_{in}W_n}{nW_i} = 5.126$
Then check the consistency:
CI = $(\lambda_{\max} - n)/(n-1)$ = $(5.126 - 5)/(5-1)$ = 0.0315
The value of RI can be obtained from Table 2, RI = 1.12
CR = CI/RI = 0.028 < 0.1
Therefore, the consistency of the matrix **A*** is satisfactory.
According to Equation (4):
$W_1{}'$ = 0.5, $W_2{}'$ = 0.1, $W_3{}'$ = 0.25, $W_4{}'$ = 0.1, $W_5{}'$ = 0.05
Therefore, the weight vector **W** = $(w_1{}', w_2{}', w_3{}' \ldots w_n{}')$ = (0.5, 0.1, 0.25, 0.1, 0.05).

*4.3. Use the FSEM to Determine the Judgment Matrix **R***

4.3.1. Residential Area Data

According to the authors' previous dam-break flood calculation results and investigation data of the Ertan Hydropower Station, 35 representative residential areas downstream of the Ertan Hydropower Station were selected for analysis. The statistical data were obtained under the most dangerous conditions of the dam break, and residential areas data are shown in Table 4.

Table 4. Residential areas data.

Num	Place Name	Population	Flood Arrival Time (h)	Flood Level (m)	Evacuation Time (h)	Local GDP (Million $)
1	Santan Village	500	0.24	147	0.267	12
2	Oufangyingdi	100	0.24	147	0.233	8
3	Gantianbao	200	0.60	144	0.50	10
4	Jinhe	200	0.60	144	0.50	26
5	Panzhihua City flooded area	129,100	1.67	138	2.0	1500
6	Xinlong Village	800	2.28	133	0.267	17.6
7	Hepiao Village	300	2.80	129.5	0.233	11
8	Yuzuo	1000	3.12	127	0.20	40
9	Lazuo	1000	3.12	127	0.233	40
10	Lumuzu	20	3.50	122	0.267	3
11	Yishala Ecological zone	200	3.70	120	0.247	11.3
12	Tuoji Factory	100	3.90	118.5	0.367	9
13	Luomodi	200	4.20	112	0.350	25
14	Yimoshidu	500	4.50	108	0.233	19
15	Jiangbian Town	800	4.74	106	0.40	75
16	Bingnong Village	100	5.22	103.5	0.40	9
17	Xikangzhi	150	5.28	103	0.433	14
18	Wande	200	5.28	103	0.667	21
19	Jiangzhu	200	5.64	100	0.564	20
20	Xinshan Village	150	6.10	96.2	0.530	10
21	Xin'an	200	6.36	95	0.636	60
22	Wumushu	40	6.85	92	0.233	3
23	Pulong	80	6.85	92	0.933	12
24	Yituzhuang	100	6.90	92.5	0.333	13
25	Luji	80	7.38	93	0.20	11
26	Longshu	30	7.62	91.6	0.60	16
27	Makou	40	7.78	89.5	0.8	5
28	Wujia Village	100	7.92	88.6	0.30	22
19	Huaizuo	50	8.39	85.3	0.56	6
30	Dalishu	100	8.55	84	0.43	24
31	Luhe Village	50	8.64	83.4	0.670	26
32	Pumie	50	8.82	82.7	0.187	21
33	Yanba	60	9.06	81	1	23
34	Yinmin	50	9.30	78	0.87	34
35	Tuobuka Town	200	9.94	74.5	0.400	60

4.3.2. Criteria for Classification of the Risk Level in Flood-Affected Areas

Due to the multiple and complex factors involved in early warning classification of flood-affected areas, the author decided to use 5-valued logical partition for evaluation according to the characteristics of mountain rivers. The author divided the risk level of the flood-affected areas into five grades: grade I is slight danger, grade II is general danger, grade III is obvious danger, grade IV is intensive danger, and grade V is extreme danger. Therefore, the evaluation set **V** can be established, $\mathbf{V} = (v_1, v_2, v_3, v_4, v_5)$ = (slight danger, general danger, obvious danger, intensive danger, extreme danger).

It is a reasonable method to classify the risk level of the flood-affected areas according to the value range of the evaluation factors. Since the smaller the value of the "flood arrival time (a_2)", the more dangerous the flood-affected area, the bigger the safety. Considering the consistency of interval assignment, we let $(10 - a_2)$ participate in the calculation as a representative factor of the flood arrival time. The 5-valued logical partition table is shown in Table 5, the interval endpoint values are represented by b_1–b_4.

Table 5. 5-value logical partition table.

Evaluation Factors and Their Assignment	Population a_1	Flood Arrival Time $(10-a_2)$	Flood Level a_3	Evacuation Time a_4	Local GDP a_5
Slight danger	≤10	≤2	≤50	≤0.4	≤10
General danger	(10)–50	(2)–4	(50)–75	(0.4)–0.5	(10)–20
Obvious danger	(50)–100	(4)–6	(75)–100	(0.5)–0.6	(20)–40
Intensive danger	(100)–(300)	(6)–(8)	(100)–(125)	(0.6)–(0.8)	(40)–(100)
Extreme danger	≥300	≥8	≥125	≥0.8	≥100

4.3.3. Quantitative Representation of Judgment Matrix R

To quantitatively express the fuzzy subset $\mathbf{R}_i$ of single factor judgment matrix **R**, the membership function table was determined according to the previous experience and the characteristics of this study, as shown in Table 6 [48,49]. According to the interval of the evaluation factors, the quantitative value of matrix **R** can be calculated by referring to the membership function Table 6 [50].

Table 6. The membership function table.

Evaluation Factor Interval	Risk Level				
	I	II	III	IV	V
$x \le b_1$	$1 - \frac{x}{2b_1}$	$\frac{x}{2b_1}$	0	0	0
$b_1 < x \le \frac{b_1+b_2}{2}$	$\frac{(b_1+b_2)-2x}{2(b_2-b_1)}$	$1 - \frac{(b_1+b_2)-2x}{2(b_2-b_1)}$	0	0	0
$\frac{b_1+b_2}{2} < x \le b_2$	0	$1 - \frac{2x-(b_1+b_2)}{2(b_2-b_1)}$	$\frac{2x-(b_1+b_2)}{2(b_2-b_1)}$	0	0
$b_2 < x \le \frac{b_2+b_3}{2}$	0	$\frac{(b_2+b_3)-2x}{2(b_3-b_2)}$	$1 - \frac{(b_2+b_3)-2x}{2(b_3-b_2)}$	0	0
$\frac{b_2+b_3}{2} < x \le b_3$	0	0	$1 - \frac{2x-(b_2+b_3)}{2(b_3-b_2)}$	$\frac{2x-(b_2+b_3)}{2(b_3-b_2)}$	0
$b_3 < x \le \frac{b_3+b_4}{2}$	0	0	$\frac{(b_3+b_4)-2x}{2(b_4-b_3)}$	$1 - \frac{(b_3+b_4)-2x}{2(b_4-b_3)}$	0
$\frac{b_3+b_4}{2} < x \le b_4$	0	0	0	$1 - \frac{2x-(b_3+b_4)}{2(b_4-b_3)}$	$\frac{2x-(b_3+b_4)}{2(b_4-b_3)}$
$x > b_4$	0	0	0	$\frac{b_4}{2x}$	$1 - \frac{b_4}{2x}$

The method of determining the membership function in the table is that when x is in a certain interval, the corresponding value of the evaluation factor is brought into the given interval to calculate; when x is at the endpoint of the interval, the value of the membership function is 0.5. Taking the relevant data from Tables 4 and 5 into Table 6 for operation, the fuzzy subset $\mathbf{R}_i$ can be obtained, thus the judgment matrix $\mathbf{R}$ of a single factor can also be determined.

4.3.4. Taking Santan Village as an Example to Calculate the Judgment Matrix **R**

(1) When the evaluation factor is the population (a_1), according to the data in Tables 4 and 5:
$x = 500$, $b_1 = 10$, $b_2 = 50$, $b_3 = 100$, $b_4 = 300$
Due to $x > b_4$, considering Table 6
$r_{11} = 0, r_{12} = 0, r_{13} = 0, r_{14} = \frac{b_4}{2x} = 0.3, r_{15} = 1 - \frac{b_4}{2x} = 0.7$
Fuzzy subset $\mathbf{R}_1 = (r_{11}, r_{12}, r_{13}, r_{14}, r_{15}) = (0, 0, 0, 0.3, 0.7)$

(2) When the evaluation factor is flood arrival time ($10-a_2$), according to the data in Tables 4 and 5:
$x = 10 - 0.24 = 9.76$, $b_1 = 2$, $b_2 = 4$, $b_3 = 6$, $b_4 = 8$
Due to $x > b_4$, considering Table 6
$r_{11} = 0, r_{12} = 0, r_{13} = 0, r_{14} = \frac{b_4}{2x} = 0.41, r_{15} = 1 - \frac{b_4}{2x} = 0.59$
Fuzzy subset $\mathbf{R}_2 = (r_{21}, r_{22}, r_{23}, r_{24}, r_{25}) = (0, 0, 0, 0.41, 0.59)$

(3) When the evaluation factor is flood level (a_3), according to the data in Tables 4 and 5:
$x = 147$, $b_1 = 50$, $b_2 = 75$, $b_3 = 100$, $b_4 = 125$
Due to $x > b_4$, considering Table 6
$r_{11} = 0, r_{12} = 0, r_{13} = 0, r_{14} = \frac{b_4}{2x} = 0.43, r_{15} = 1 - \frac{b_4}{2x} = 0.57$
Fuzzy subset $\mathbf{R}_3 = (r_{31}, r_{32}, r_{33}, r_{34}, r_{35}) = (0, 0, 0, 0.43, 0.57)$

(4) When the evaluation factor is evacuation time (a_4), according to the data in Tables 4 and 5:
$x = 147$, $b_1 = 50$, $b_2 = 75$, $b_3 = 100$, $b_4 = 125$
Due to $x > b_4$, considering Table 6
$r_{41} = 1 - \frac{x}{2b_1} = 0.67, r_{42} = \frac{x}{2b_1} = 0.33, r_{43} = 0, r_{44} = 0, r_{45} = 0$
Fuzzy subset $\mathbf{R}_4 = (r_{41}, r_{42}, r_{43}, r_{44}, r_{45}) = (0.67, 0.33, 0, 0, 0)$

(5) When the evaluation factor is local GDP (a_5), according to the data in Tables 4 and 5:
$x = 1.2$, $b_1 = 1$, $b_2 = 2$, $b_3 = 4$, $b_4 = 10$
Due to $b1 < x \leq \frac{b1 + b2}{2}$, considering Table 6
$r_{51} = \frac{(b_1 + b_2) - 2x}{2(b_2 - b_1)} = 0.3, r_{52} = 1 - \frac{(b_1 + b_2) - 2x}{2(b_2 - b_1)} = 0.7, r_{53} = 0, r_{54} = 0, r_{55} = 0$
Fuzzy subset $\mathbf{R}_5 = (r_{51}, r_{52}, r_{53}, r_{54}, r_{55}) = (0.3, 0.7, 0, 0, 0)$

Therefore, the judgment matrix $\mathbf{R} = (\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3, \mathbf{R}_4, \mathbf{R}_5)$, $\mathbf{R}$ can also be expressed as:

$$\mathbf{R} = \begin{pmatrix} 0 & 0 & 0 & 0.3 & 0.7 \\ 0 & 0 & 0 & 0.41 & 0.59 \\ 0 & 0 & 0 & 0.43 & 0.57 \\ 0.67 & 0.33 & 0 & 0 & 0 \\ 0.3 & 0.7 & 0 & 0 & 0 \end{pmatrix}$$

5. Discussion and Results

5.1. Santan Village

The fuzzy decision of a multi-objective system can be represented by $\mathbf{B} = \mathbf{W} \bullet \mathbf{R}$, where $\mathbf{B}$ represents the fuzzy comprehensive evaluation set. As can be seen from Section 4.2.3, the weight vector $\mathbf{W} = (w_1{}',$

$w_2{}'$, $w_3{}'$ ... $w_n{}'$) = (0.5, 0.1, 0.25, 0.1, 0.05), the judgment matrix **R** has been calculated in Section 4.3.4, so set **B** can be calculated.

$$\mathbf{B} = \mathbf{W}\cdot\mathbf{R} = (0.5,\ 0.1,\ 0.25,\ 0.1,\ 0.05)\cdot\begin{pmatrix} 0 & 0 & 0 & 0.3 & 0.7 \\ 0 & 0 & 0 & 0.41 & 0.59 \\ 0 & 0 & 0 & 0.43 & 0.57 \\ 0.67 & 0.33 & 0 & 0 & 0 \\ 0.3 & 0.7 & 0 & 0 & 0 \end{pmatrix} = (0.08,\ 0.07,\ 0,\ 0.3,\ 0.55)$$

Therefore, the risk level of Santan Village is shown in Table 7.

Table 7. The risk level of Santan Village.

Slight Danger	General Danger	Obvious Danger	Intensive Danger	Extreme Danger
0.08	0.07	0	0.3	0.55

According to the maximum membership principle, the maximum value corresponds to the risk level in the area, so the risk level of Santan Village is extreme danger.

5.2. Panzhihua City Flooded Area

After the Ertan Hydropower Station dam broke, the flood mainly inundated part of the eastern region of Panzhihua city. As Panzhihua is an industrial city, the population density is relatively large, so once the dam-break flood occurs, it will cause huge casualties and property losses, therefore, it is necessary to calculate the risk level of the Panzhihua city flooded area. The calculation process is referred to in Section 4.3.4.

(1) When the evaluation factor is the population (a_1):
Fuzzy subset $\mathbf{R}_1$ = (r_{11}, r_{12}, r_{13}, r_{14}, r_{15}) = (0, 0, 0, 0, 1)
(2) When the evaluation factor is flood arrival time (10−a_2):
Fuzzy subset $\mathbf{R}_2$ = (r_{21}, r_{22}, r_{23}, r_{24}, r_{25}) = (0, 0, 0, 0.48, 0.52)
(3) When the evaluation factor is flood level (a_3):
Fuzzy subset $\mathbf{R}_3$= (r_{31}, r_{32}, r_{33}, r_{34}, r_{35}) = (0, 0, 0, 0.45, 0.55)
(7) When the evaluation factor is evacuation time (a_4):
Fuzzy subset $\mathbf{R}_4$ = (r_{41}, r_{42}, r_{43}, r_{44}, r_{45}) = (0, 0, 0, 0.2, 0.8)
(5) When the evaluation factor is local GDP (a_5):
Fuzzy subset $\mathbf{R}_5$ = (r_{51}, r_{52}, r_{53}, r_{54}, r_{55}) = (0, 0, 0, 0.03, 0.97)

Therefore, the judgment matrix **R** = ($\mathbf{R}_1$, $\mathbf{R}_2$, $\mathbf{R}_3$, $\mathbf{R}_4$, $\mathbf{R}_5$), **R** can also be expressed as:

$$\mathbf{R} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.48 & 0.52 \\ 0 & 0 & 0 & 0.45 & 0.55 \\ 0 & 0 & 0 & 0.2 & 0.8 \\ 0 & 0 & 0 & 0.03 & 0.97 \end{pmatrix}$$

As can be seen from Section 4.2.3, the weight vector **W** = ($w_1{}'$, $w_2{}'$, $w_3{}'$ ... $w_n{}'$) = (0.5, 0.1, 0.25, 0.1, 0.05), so the set **B** can be calculated, **B** = **W**•**R** = (0, 0, 0, 0.18, 0.82). Therefore, the risk level of the Panzhihua City flooded area is shown in Table 8.

Table 8. The risk level of the Panzhihua City flooded area.

Slight Danger	General Danger	Obvious Danger	Intensive Danger	Extreme Danger
0	0	0	0.18	0.82

The risk level of the Panzhihua City flooded area is: Extreme danger.

5.3. Other Flood-Affected Areas

The risk level of other flood-affected areas can be calculated by the above method; the calculation process is omitted, and the results are shown in Table 9.

Table 9. The risk level of flood-affected areas.

Num	Place Name	Fuzzy Comprehensive Evaluation Set B	Grade	Risk Level
1	San Tan Village	0.08, 0.07, 0.00, 0.30, **0.55**	V	Extreme danger
2	Oufangyingdi	0.10, 0.05, 0.25, **0.40**, 0.20	IV	Intensive danger
3	Gantianbao	0.03, 0.08, 0.05, **0.65**, 0.20	IV	Intensive danger
4	Jinhe	0.00, 0.06, 0.09, **0.65**, 0.20	IV	Intensive danger
5	Panzhihua City	0.00, 0.00, 0.00, 0.18, **0.82**	V	Extreme danger
6	Xinlong Village	0.07, 0.07, 0.01, 0.28, **0.57**	V	Extreme danger
7	Hepiao Village	0.09, 0.06, 0.00, **0.46**, 0.39	IV	Intensive danger
8	Yuzuo	0.08, 0.03, 0.03, 0.32, **0.55**	V	Extreme danger
9	Lazuo	0.07, 0.03, 0.03, 0.32, **0.55**	V	Extreme danger
10	Lumuzu	0.23, **0.42**, 0.03, 0.23, 0.10	II	General danger
11	Yishala Ecological zone	0.09, 0.06, 0.04, **0.74**, 0.08	IV	Intensive danger
12	Tuoji Factory	0.08, 0.07, 0.30, **0.50**, 0.06	IV	Intensive danger
13	Luomodi	0.06, 0.06, 0.10, **0.79**, 0.00	IV	Intensive danger
14	Yimoshidu	0.07, 0.06, 0.14, **0.38**, 0.35	IV	Intensive danger
15	Jiangbian Town	0.05, 0.05, 0.15, 0.34, **0.41**	V	Extreme danger
16	Bingnong Village	0.08, 0.08, **0.43**, 0.41, 0.00	III	Obvious danger
17	Xikangzhi	0.02, 0.14, 0.31, **0.53**, 0.00	IV	Intensive danger
18	Wande	0.00, 0.04, 0.23, **0.74**, 0.00	IV	Intensive danger
19	Jiangzhu	0.00, 0.06, 0.30, **0.64**, 0.00	IV	Intensive danger
20	Xinshan Village	0.03, 0.10, 0.41, **0.46**, 0.00	IV	Intensive danger
21	Xin'an	0.00, 0.07, 0.25, **0.68**, 0.00	IV	Intensive danger
22	Wumushu	0.11, **0.50**, 0.34, 0.05, 0.00	II	General danger
23	Pulong	0.02, 0.13, **0.66**, 0.14, 0.06	III	Obvious danger
24	Yituzhuang	0.07, 0.18, **0.46**, 0.30, 0.00	III	Obvious danger
25	Luji	0.11, 0.14, **0.65**, 0.11, 0.00	III	Obvious danger
26	Longshu	0.03, **0.61**, 0.26, 0.09, 0.00	II	General danger
27	Makou	0.08, **0.45**, 0.36, 0.07, 0.05	II	General danger
28	Wujia Village	0.11, 0.11, **0.52**, 0.26, 0.00	III	Obvious danger
29	Huaizuo	0.09, 0.33, **0.57**, 0.01, 0.00	III	Obvious danger
30	Dalishu	0.08, 0.17, **0.50**, 0.25, 0.00	III	Obvious danger
31	Luhe Village	0.07, 0.34, **0.51**, 0.09, 0.00	III	Obvious danger
32	Pumie	0.15, 0.37, **0.48**, 0.00, 0.00	III	Obvious danger
33	Yanba	0.08, 0.26, **0.57**, 0.04, 0.06	III	Obvious danger
34	Yinmin	0.08, 0.36, **0.45**, 0.06, 0.05	III	Obvious danger
35	Tuobuka Town	0.15, 0.18, 0.13, **0.54**, 0.00	IV	Intensive danger

The risk level of a flood-affected area can be directly expressed on the flood risk map Figure 4.

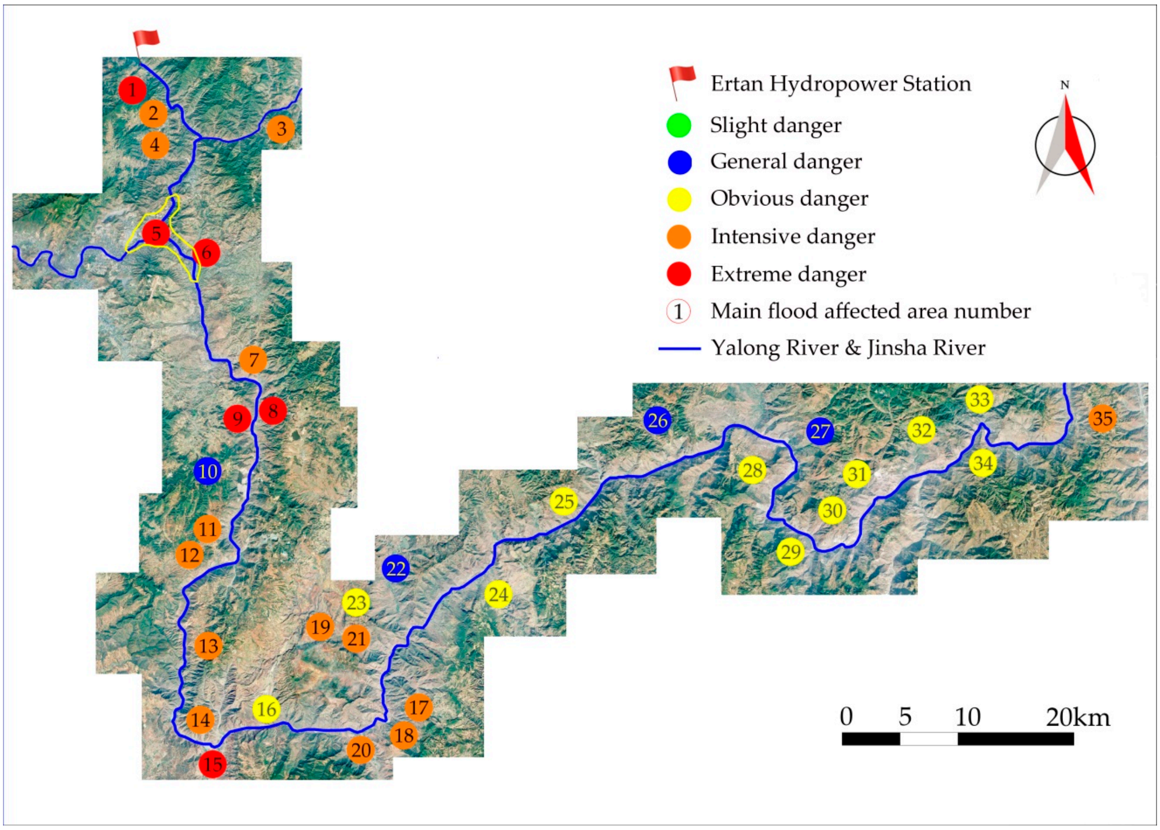

Figure 4. Flood risk map.

When the Ertan Hydropower Station dam break occurs, the competent department can evacuate and rescue the local people in time according to the risk map of the flood-affected areas.

5.4. Applications of Study Results

In this study, the FAHP method was applied to evaluate the flood risk level at 35 flood-prone locations downstream of Ertan hydropower dam in Southwest China. Although there has never been a dam-break accident in Ertan Hydropower Station since its completion, the areas with a higher risk level in the past few years had a greater adverse impact on the safety of people and property during the flood season. We will test our study results with the examples of Quxue Hydropower Station and Guanmaozhou Hydropower Station.

5.4.1. Quxue Hydropower Station

The Quxue Hydropower Station is in Derong County, Ganzi Tibetan Autonomous Prefecture, Sichuan Province in Southwest China. The dam is a rockfill dam with asphalt concrete core with a maximum dam height of 165.2 m and a total reservoir capacity of 132,600,000 m^3. This Hydropower Station was completed in 2016, and the water gate was destroyed by the flood after the first water storage in the flood season. We conducted a detailed dam-break flood risk study and investigated ten representative villages and towns downstream of the dam. The FAHP method was used to evaluate the risk level of the ten typical villages and towns. The results are shown in Table 10.

Table 10. The risk level of flood-affected areas.

Num	Place Name	Risk Level	Num	Place Name	Risk Level
1	Maowu Village	Extreme danger	6	Guxue Town	Obvious Danger
2	Rizhong Village	Intensive danger	7	Deze Village	General Danger
3	Riding Village	Intensive danger	8	Qugangding Village	General Danger
4	Xiayong Village	Obvious Danger	9	Benzilan Town	Slight Danger
5	Biyong Village	Obvious Danger	10	Zigeng Town	Slight Danger

According to the flood situation in the flood season from 2017 to 2018, the three villages with a higher risk level had experienced different degrees of casualties and property losses; the villages with a lower risk level endured the flood safely. Being a smaller, less-populated village, the Maowu Village with highest-risk has been resettled.

5.4.2. Guanmaozhou Hydropower Station

The Guanmaozhou Hydropower Station is in Mabian County, Leshan City, Sichuan Province in Southwest China. The dam is an earth-rock Dam with an asphalt concrete core with a maximum dam height of 108 m and a total reservoir capacity of 97,330,000 m^3. This power station was completed and put into operation in September 2015. It has been tested by two major floods in 2017 and 2018. The dam flood discharge has caused a certain degree of adverse impact on downstream villages and towns. Eight typical villages and towns were chosen. The results calculated by the FAHP method are shown in Table 11.

Table 11. The risk level of flood-affected areas.

Num	Place Name	Risk Level	Num	Place Name	Risk Level
1	Suba Town	Extreme danger	5	Tongkuangxi Village	Obvious Danger
2	Xiaojiangzi Village	Intensive danger	6	Tianjiashan Village	Obvious Danger
3	Yangba Village	Intensive danger	7	Tiaodungou Village	General Danger
4	Yaomoping Village	Intensive danger	8	Jianshe Town	General Danger

According to the flood feedback in recent years, there was no major flood in 2016, the Guanhuzhou Hydropower Station operated well, and the downstream villages and towns were not affected by the flood. A big flood occurred in two consecutive years in 2017 and 2018. The downstream villages and towns have been affected by the flood discharge from the Hydropower Station; the higher the risk level, the greater the losses suffered. Fortunately, there were no casualties.

It can be seen that the FAHP method has important application values in assessing the risk and providing an early warning to the flood-affected area when a dam break occurs.

6. Conclusions

The Ertan Hydropower Station is the largest hydropower station built and put into operation in China in the 20th century. Due to the dam being high with a large storage capacity, once the dam breaks in the case of heavy rain, earthquake, mountain collapse, war, or terrorist activities, it will cause a great number of casualties and property losses to the downstream cities and towns. Therefore, it is necessary and urgent to study the dam-break flood of the Ertan Hydropower Station. According to the existing results of dam-break flood calculation, the authors selected 35 main flood-affected areas as the research objects and focused on the calculation of risk level in these 35 regions. The Ertan Hydropower Station is in the mountain river in Southwest China, where the process of runoff yield and flow concentration is extremely complex, and the meteorology, hydrology, geography, social activity, and industry are fuzzy and difficult to quantify. To solve these problems, the author established a complete mathematical model based on FAHP in this study.

The author constructed a fuzzy comprehensive evaluation index system by using FAHP, and selected five characteristic factors: the population, flood arrival time, flood level, evacuation time, and local GDP as the evaluation factors to evaluate the flood-affected areas. FAHP can be divided into AHP and the FSEM. Firstly, the importance of the relationship between the five evaluation factors can be calculated by using AHP, and the weight vector **W** can be obtained. Secondly, the principle of fuzzy transform and the maximum membership of FSEM can be used to determine the judgment matrix **R** of the individual evaluation factor. Finally, the fuzzy comprehensive evaluation set **B** can be calculated according to the fuzzy decision principle of a multi-objective system, **B** = **W•R**. Set **B** contains five factors, the maximum factor corresponds to the risk level of the flood-affected area, so the risk level of the 35 flood-affected areas can be calculated quantitatively one by one.

The author applied this study's results to other hydropower stations; Quxue and Guanmaozhou Hydropower Station were selected as two examples for analysis. According to the flood feedback in recent years, it can be seen that the FAHP has important application values in risk assessment and early warning of the flood-affected area when a dam breaks. The application of this study's results has upgraded the qualitative flood evaluation stage to such a point that quantitative calculations can be carried out. Since flood risk management is a huge system, this study only discussed the risk level of the flood-affected areas, and quantitatively described the risk level of the affected area. Further research should be done into the evacuation of disaster victims and the selection of shelter sites.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/10/1369/s1. Supplementary File: dam-break flood calculation results and investigation data of the Ertan Hydropower Station.

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