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Fuzzy Risk Evaluation and Application of Water Supply System in Mountain Areas

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Water supply system is the infrastructure to ensure the steady economic growth in mountainous areas. According to the characteristics of water supply system in a mountainous area of North China and on the basis of risk source identification, this study establishes a comprehensive risk system of water supply system by selecting 6 links such as water pollution, water pipeline, water treatment chemical residues, natural geology, project management, and tourism area impact and 23 sub-risk factors, and calculates the weight of each factor. The comprehensive evaluation is obtained by combining expert scoring. After evaluation, the risk level of the water supply system is general, and chemical pollution of water source and chemical residues of water treatment are high-level risk factors, which need to be strictly controlled.

1. Research background

Since the Nineteenth National Congress of the Communist Party of China, vigorous development of tourism through changing the mode of economic growth has brought multiple benefits for green economic growth and precise poverty eradication in mountainous areas, which puts forward higher requirements for water supply construction in mountainous tourist areas. On the one hand, the healthy development of mountain economy and society is inseparable from the safe, stable and efficient water supply system; on the other hand, the construction and operation of water supply system will bring potential ecological and environmental damage risks to mountain areas (Guo and Yang, 2018). Especially for the mountainous areas where tourism is the main mode of development, water supply security is more needed. Therefore, risk assessment and management of mountain water supply system is of great significance to improve the risk management and control level of water supply system in specific environment, to ensure the safe operation of water supply system and to maintain the ecological environment.

According to the characteristics of mountain water supply system, this study involves the risk source identification, and constructs the risk assessment model of mountain water supply system based on fuzzy analytic hierarchy process according to the risk assessment principle. Finally, this study carries out the risk assessment of mountain water supply system in North China and obtains the corresponding assessment results.

2. Analytic hierarchy process and the basic principle of membership degree determination

Based on network system theory and multi-objective comprehensive evaluation, the Analytic Hierarchy Process (AHP) decomposes a complex object into several levels of multiple objects, and calculates the single ranking (weight) and total ranking of each level by fuzzy quantitative method of qualitative index. It is a systematic method of objective (multi-index) and multi-scheme optimization decision-making. The method is simple, flexible and universally practical. The AHP method is divided into four steps: firstly, establish the hierarchical structure model; secondly, comparative judgment matrix is constructed. Thirdly, calculate the maximum eigenvalue of comparison judgment matrix and its corresponding eigenvectors; finally, carry out hierarchical ranking and consistency checking (Tesfamariam and Sadiq, 2006).

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2.1 Establish the hierarchical structure model

Based on the analysis of the characteristics of mountain water supply system, the mountain water supply system is divided into three levels, namely, the target level (A level), that’s, the comprehensive risk of mountain water supply system; criteria level (B level), including water pollution, water pipeline, water treatment chemical residues, natural geology, project management, and tourism area impact. Criteria level determines the comprehensive risk level of water supply system, and its impact mode needs to be reflected through the specific factors related to it, which is the intermediate link to solve the problem; decision-making level (C-level), in which the criteria layer will be refined to each specific control factors, and the comprehensive risk assessment of water supply system can be completed through the analysis and solution of specific problems (Gaudenzi and Borghesi, 2006; Olivier-Maget and Hetreux , 2016; Tirmizi and Tirmizi, 2018)

2.2 Construct the index system

According to the characteristics of mountain water supply system, six criteria-level indexes such as water pollution, water pipeline, water treatment chemical residues, natural geology, project management, and tourism area impact, are selected under the principles of scientificity, comprehensiveness, representativeness and systematicness of index selection. The decision-making factors of each index are as follows:

(1) Water supply source link. The situation of water supply source is complicated with many risk factors, which are difficult to be managed and protected. Some protective measures can reduce the risk probability, but there are many uncertain factors, such as chemical pollution of water body and chemical pollution around the water source, which will cause great damage to the water supply system.

(2) Water supply system link. As the most important part of the water supply system, the water supply system, including the pump station and the pipeline, has great risks due to the complexity of the water supply project and the difficulty of management.

(3) The water treatment link is a process of converting the incoming water from the water source into the water conforming to the user's standard, so the link directly determines whether the water quality of the water supply is qualified or not, and the risk level of the link is mainly composed of the water treatment process and the chemical residues of the water treatment.

(4) There are many deep-cut loess gullies along the water supply pipeline in mountainous areas, and the loess is slightly collapsible in local areas, which results in the uneven settlement of longer water supply pipeline, so the reinforcement measures should be taken.

(5) The project management risk mainly comes from safety inspection and supervision, safety hazard rectification, safety management system, accident emergency repair plan, etc.

(6) Because the water supply system is located in mountainous areas, the natural environment in mountainous areas may be damaged by the water source place and the engineering construction.

The six important factors mentioned above are taken as the criterion level and subdivided into 23 influencing factors as the third level to construct the comprehensive risk assessment system of water supply, as shown in Figure 1.

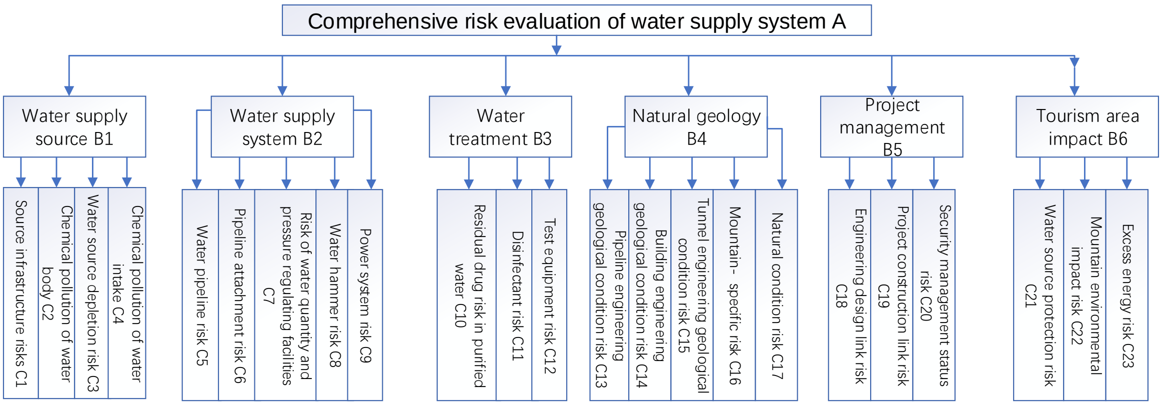

Figure 1: Index system of comprehensive risk evaluation of water supply system

2.3 Fuzzy comprehensive evaluation path

Fuzzy comprehensive evaluation is a comprehensive evaluation method based on fuzzy mathematics (Xu et al., 2013; Saade and Schwarzlander, 1992). The basic idea of fuzzy comprehensive risk assessment of water supply system is synthetically considering the influence degree of all factors and adopting AHP to determine the weight of each factor in order to distinguish its relative importance; finally, calculate the impact possibility of the various factors with a mathematical model, in which the factor with great possibility is the final value of difficulty.

The main steps of multilevel fuzzy comprehensive evaluation:

(1) Determine the evaluation indexes and corresponding weights.

(2) Establish an evaluation result set V, which is the same as that in the single-level fuzzy comprehensive evaluation, V={v1, v2, ⋯⋯, vn}.

(3) Carry on the comprehensive evaluation of the first-level index, namely carry on the comprehensive evaluation according to each factor in a certain category. Let the *i*-th (*i*=1, 2 … n) factor be evaluated comprehensively, and the membership matrix of the *k*-th (*k*=1, 2 … m) factor belonging to the evaluation result set is as follows:

$$R_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots r_{i1m} \\ r_{i21} & r_{i22} & \cdots r_{i2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{in1} & r_{in2} & \cdots r_{inm} \end{bmatrix}$$

So the fuzzy comprehensive evaluation set of the *i*-th factor is:

$$B_i = W_i \cdot R_i = (W_{i1} + W_{i2} \cdots W_{in}) \cdot \begin{pmatrix} r_{i11} & \cdots & r_{i1m} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{inm} \end{pmatrix} = b_{i1}, b_{i2}, \dots, b_{im}$$

Where i=1, 2...n, Bi is the result of calculating the factors of the *i*-th index included in the B-th level relative to its superior factors, bi is the weight of each subordinate factor relative to the *i*-th index of the B-level, and Ri is a fuzzy evaluation matrix.

Conduct comprehensive evaluation of secondary factors

The evaluation matrix shall be the lowest level fuzzy comprehensive evaluation matrix:

$B = W \cdot (B1B2 \cdots Bn)^T = (w1w2 \cdots wn) \cdot (B1B2 \cdots Bn)^T$

3. Mountain water supply system index weight and consistency test

3.1 Construct judgment matrix

The weight value of risk evaluation indexes of mountain water supply system is calculated with analytic hierarchy process (AHP). After the index system is determined, the judgment matrix is constructed with 1 ~ 9 comparison scale. Judgment matrix is a quantitative matrix that characterizes the importance of the elements at this level relative to the upper level. In the judgment matrix A, b_{ij} indicates the relative importance of b_i to b_j,b_{ij} generally takes 1, 2, …, 9 and its reciprocal, b_{ij}=1 indicates that elements i and j are equally important, b_{ij}=3 indicates that the element i is slightly more important than j, and so on, b_{ij}=9 indicates that the element i is extremely important than j. The judgment matrix satisfies: b_{ii}=1 and b_{ij}=1/b_{ji}.

When 1 ~ 9 comparison scale is used to construct the judgment matrix, the importance of water supply source in the judgment matrix is 1/3 more than that of water delivery system, that's, the value of element a_{12} in matrix A is 1/3; as the water supply source link is of the same importance to the comprehensive risk of the water supply system as the tourist area, i.e. the value of a_{16} is 1. Similarly, by comparing the importance of other elements, the comparison judgment matrix of comprehensive risk of water supply system is constructed:

$$A = \begin{bmatrix} 1 & \frac{1}{3} & \frac{4}{6} & 2 & \frac{4}{10} & 1 \\ 3 & 1 & 2 & 6 & \frac{12}{10} & 3 \\ \frac{6}{4} & \frac{6}{12} & 1 & 3 & \frac{6}{10} & \frac{6}{4} \\ \frac{2}{4} & \frac{2}{12} & \frac{2}{6} & 1 & \frac{2}{10} & \frac{2}{4} \\ \frac{10}{4} & \frac{10}{12} & \frac{10}{6} & 5 & 1 & \frac{10}{4} \\ 1 & \frac{4}{12} & \frac{4}{6} & 2 & \frac{4}{10} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of the water supply source link B_1 by the same method:

$$A=\begin{bmatrix} 1 & \frac{4}{9} & 2 \\ \frac{9}{4} & 1 & \frac{9}{2} \\ \frac{1}{2} & \frac{2}{9} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of water delivery system link B_2 by the same method:

$$A=\begin{bmatrix} 1 & \frac{3}{12.5} & \frac{3}{11} & \frac{3}{9} & \frac{3}{12} & \frac{3}{5} \\ \frac{12.5}{3} & 1 & \frac{12.5}{11} & \frac{12.5}{9} & \frac{12.5}{12} & \frac{12.5}{5} \\ \frac{11}{3} & \frac{11}{12.3} & 1 & \frac{11}{9} & \frac{11}{12} & \frac{11}{5} \\ 3 & \frac{9}{12.5} & \frac{9}{11} & 1 & \frac{9}{12} & \frac{9}{5} \\ 4 & \frac{12}{12.5} & \frac{12}{11} & \frac{12}{9} & 1 & \frac{12}{5} \\ \frac{5}{3} & \frac{5}{12.5} & \frac{5}{11} & \frac{5}{9} & \frac{5}{12} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of the water treatment link B_3 by the same method:

$$A=\begin{bmatrix} 1 & \frac{2}{6} & \frac{2}{8} \\ 3 & 1 & \frac{6}{8} \\ 4 & \frac{8}{6} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of natural geological link B_4 by the same method:

$$A=\begin{bmatrix} 1 & \frac{1}{1.5} & \frac{1}{2} & \frac{1}{10.5} & \frac{1}{2} \\ 1.5 & 1 & \frac{1.5}{2} & \frac{1.5}{10.5} & \frac{1.5}{2.5} \\ 2 & \frac{2}{1.5} & 1 & \frac{2}{10.5} & \frac{2}{2.5} \\ 10.5 & \frac{10.5}{1.5} & \frac{10.5}{2} & 1 & \frac{10.5}{2.5} \\ 2.5 & \frac{2.5}{1.5} & \frac{2.5}{2} & \frac{2.5}{10.5} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of project management link B_5 by the same method:

$$A=\begin{bmatrix} 1 & \frac{2}{12} & \frac{2}{11} \\ 6 & 1 & \frac{12}{11} \\ \frac{11}{2} & \frac{11}{12} & 1 \end{bmatrix}$$

Determine the comparison judgment matrix of tourist area impact B_6 by the same method:

$$A=\begin{bmatrix} 1 & \frac{6}{4.5} & \frac{6}{9.5} \\ \frac{4.5}{6} & 1 & \frac{4.5}{9.5} \\ \frac{9.5}{6} & \frac{9.5}{4.5} & 1 \end{bmatrix}$$

3.2 Consistency check and total hierarchical rank

As the elements in the judgment matrix are estimated, there are some subjective factor which are not very accurate, and each element of the comparison judgment matrix cannot satisfy:
$a_{ij}=a_{ij}\cdot a_{ij}$, $CI=(\lambda max-n)/(n-1)$
So, it's necessary to carry out the consistency check, which performed by calculating consistency indexes, and consistency ratio, which is
$CR=CI/RI$

If the consistency ratio CR is less than 0.10, the consistency in the comparison judgment matrix is considered acceptable, and the weight vector W is considered acceptable.

Maple is used to calculate the maximum eigenvalue λmax of each judgment matrix and its corresponding eigenvector W_i (i=1, 2, …, 5). The eigenvector is normalized to get Wi. Then the consistency is checked with CR method.

It is verified that the CR values of all the matrices are all satisfied with CR<0.1, so they are consistent.

According to the above calculation, the weights of the risk factors of each link of the water supply system are shown in Table 1.

Table 1: Risk weights of water supply system

Target level A	Criterion level B	Index level C	Comprehensive weight A(B×C)
Water Supply System Risk	Water supply source B_1(0.105)	Source infrastructure risk C_1(0.267)	0.028
		Chemical pollution of water source C_2(0.600)	0.063
		Water source depletion risk C_3(0.133)	0.014
	Water supply system B_2(0.316)	Chemical pollution of water intake C_4(0.057)	0.006
		Water pipeline risk C_5(0.238)	0.075
		Pipeline attachment risk C_6(0.210)	0.066
		Risk of water quantity and pressure regulating facilities C_7(0.171)	0.054
		Water hammer risk C_8(0.229)	0.072
		Test equipment risk C_9(0.095)	0.030
	Water treatment B_3(0.106)	Residual drug risk in purified water C_{10}(0.125)	0.013
		Risk of storage of chemical agents C_{11}(0.375)	0.039
		Electricity, electrical and mechanical facilities risk C_{12}(0.500)	0.053
	Natural geology B_4 (0.053)	Pipeline engineering geological condition risk C_{13}(0.060)	0.003
		Building engineering geological condition risk C_{14}(0.086)	0.005
		Tunnel engineering geological condition risk C_{15}(0.114)	0.006
		Special risk of winter water transfer project in mountainous area C_{16}(0.598)	0.032
		Natural condition risk C_{17}(0.142)	0.008
	Project management B_5(0.263)	Engineering design link risk C_{18}(0.080)	0.021
		Project construction link risk C_{19}(0.480)	0.126
		Security management status risk C_{20}(0.440)	0.116
	Tourism area impact B_6(0.158)	Water source protection risk C_{21}(0.125)	0.013
		Mountain environmental impact risk C_{22}(0.375)	0.039
		Excess energy risk C_{23}(0.500)	0.053

4. Establishment and test of fuzzy relation

4.1 Determine membership

Qualitative indexes refer to indexes that cannot be quantified but can only be described by words in terms of degree. Here, the risk level is qualitatively described as small, general, great and serious. Percentage statistics method can be adopted, and it directly counts the percentage of the evaluation results of the evaluation object, takes the results as the membership of the index, and constructs the risk source evaluation matrix of each factor.

4.2 Establish risk source evaluation matrix

According to the risk value assessment results of each risk source, the experts evaluate each risk with risk levels and obtain the fuzzy relation matrix R, as shown in Table 2.

Table 2: Risk source evaluation matrix R of water supply system

Small	General	Great	Serious
1	0	0	0
0	0.5	0.5	0
1	0	0	0
1	0	0	0
0	0	0	1
0	1	0	0
0	0	1	0
0	0	0	1
0.25	0.75	0	0
0	1	0	0
0.5	0.5	0	0
0	0.75	0.25	0
1	0	0	0
1	0	0	0
1	0	0	0
0	0	0	1
1	0	0	0
1	0	0	0
0	0.5	0.5	0
0	0.25	0.75	0
1	0	0	0
0	1	0	0
0	1	0	0

4.3 Comprehensive evaluation of mountain water supply system

The result of the fuzzy comprehensive evaluation is as follows: B=A×R={0.1295, 0.42525, 0.25425, 0.179}.
After normalization, the following is obtained: B={0.131, 0.431, 0.257, 0.181}.
According to the maximum principle of membership function and corresponding elements in the evaluation set V, the risk level of mountain water supply system is general.

5. Conclusions

Mountain water supply system is located in a harsh environment with fragile ecology, so there is a high demand for water supply project construction and management. In order to improve the safe operation level of mountain water supply system, the analytic hierarchy process is used for fuzzy evaluation, and the results show that there are some risks in the system, among which, the risks caused by three factors such as the destruction of surrounding ecological environment, the leakage of chemical pollutants from water source and the residues of chemical agents in water treatment are the greatest, and the corresponding risk management countermeasures should be taken to reduce the losses caused by the risks.

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