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Operational safety risk assessment of water diversion infrastructure based on FMEA with fuzzy inference system

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ABSTRACT

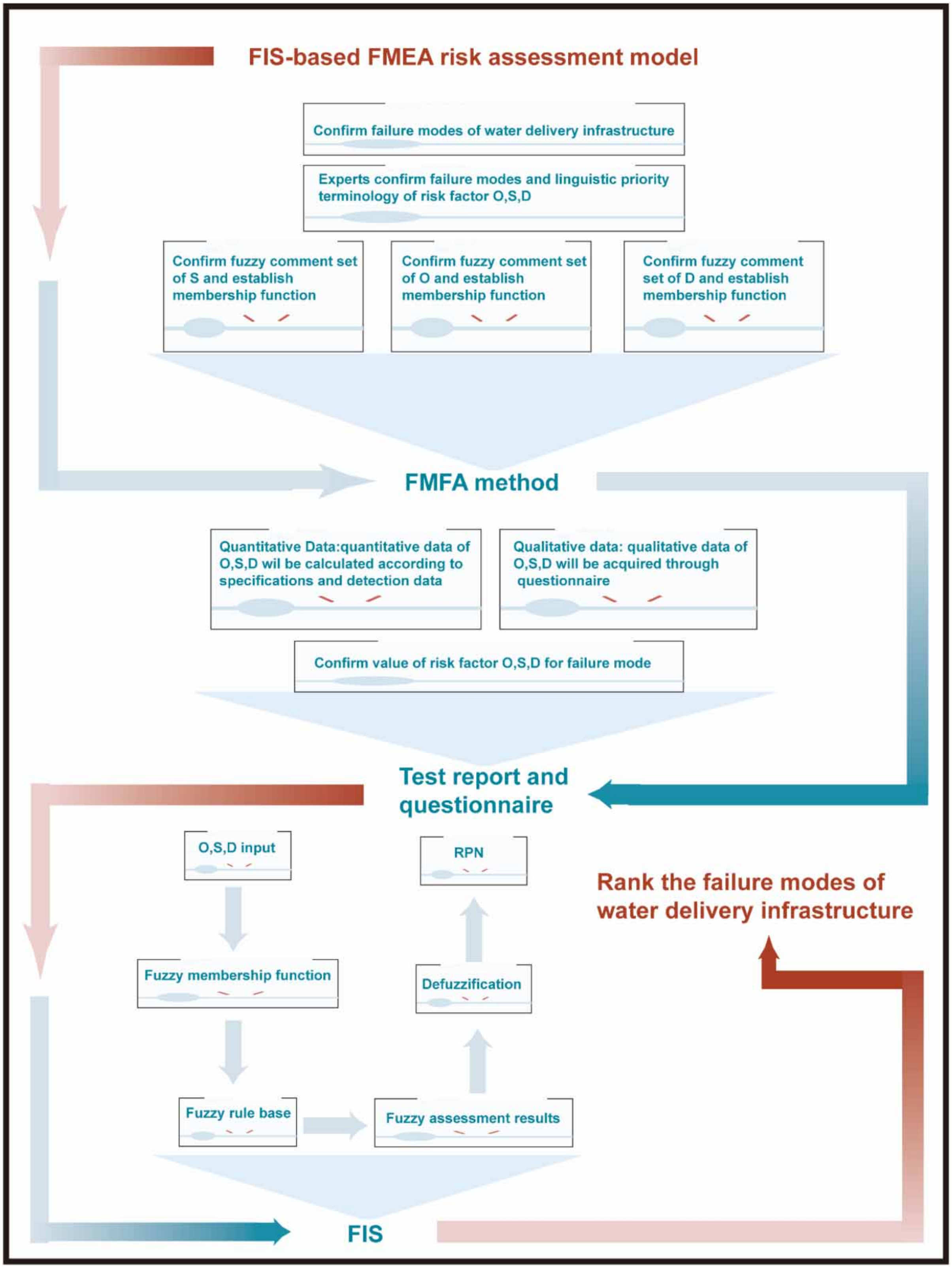
Water diversion infrastructure is characterized by a wide range of impacts and complex geological conditions. There are a large number of risk factors that affect its operational safety. Accidents that have occurred during operation have caused devastating disasters to water diversion infrastructure. In this study, the failure modes for the operational risks of water diversion infrastructure are identified from four aspects, i.e.,environment, engineering technology, operation management, and society. A failure mode and effect analysis (FMEA) risk poiorization model is established based on the fuzzy inference system (FIS). A fuzzy rule base is established according to IF-THEN rules, and the risk priority is calculated and ranked via FIS. Lastly, a case study of the Huixian section of the Middle Route of the South-to-North Water Transfer Project is carried out to verify the proposed method. The results show that the risks of rainstorms, floods, and foundation failure are regarded as high priority. The validity and applicability of the proposed method are tested via comparison with traditional FMEA. These findings provide valuable information for the operational safety of water diversion infrastructure.

Key words: failure mode and effect analysis (FMEA), fuzzy inference system (FIS), risk prioritization, water diversion infrastructure

HIGHLIGHTS

- Operational safety failure modes of water diversion infrastructure were identified in four areas: environmental, engineering, operational management, and social.
- A risk prioritization model of FMEA is established that is based on Fuzzy Inference System (FIS).
- A fuzzy rule base is established according to IF-THEN rules, and the risk priority is calculated and ranked via a FIS.

GRAPHICAL ABSTRACT



LIST OF ABBREVIATIONS

FMEA	Failure mode and effect analysis
FIS	Fuzzy inference system
RPN	Risk priority number
MRP-SNWDP	The middle route project of the South-to-North Water Diversion Project
O	Occurrence of failure modes
S	Severity of failure modes
D	Detection difficulty of failure modes

1. INTRODUCTION

Water diversion infrastructure can effectively alleviate the imbalance of water resources distribution, optimize water resource allocation, and promote coordinated regional development. It also plays an important role in water supply, agricultural development, energy production (Adeniran *et al.* 2021). However, water diversion infrastructure generally has a long construction period, entailing a huge volume of work and involving many parties, and numerous risk factors that are difficult to identify (He *et al.* 2018). In the event of a safety incident, the consequences can be unimaginable. To ensure the safe and efficient operation of water diversion facilities and water safety, it is necessary to analyze and assess the operational safety risks of water diversion infrastructures (Wang 2021).

There are many studies on failure mode recognition. Xiong *et al.* (2010) systematically analyzed the set of system failure modes in long-distance water diversion projects. From the perspective of source, natural risks include floods, rainstorms, and earthquakes, while human-made risks are from water quality pollution and improper maintenance behavior. Furthermore, nine fault models were recognized, such as overturning and slippage, leakage damage, structural accidents, etc. He *et al.* (2018) investigated relevant risk factors and their interrelationships for large water projects through a literature review and interviews representing stakeholder perspectives, identifying key social stability risk factors based on social network analysis. Nie *et al.* (2019) identified six types of operational safety risks, including engineering risks, hydrological risks, water quality pollution risks, social risks, economic risks, and operation schedule risks. Zhao *et al.* (2018) identified the risk factors of the South-to-North Water Diversion Project in Shandong Province via a checklist method. Most previous studies have been qualitative in nature, focusing on specific failure modes of typical structures. Few studies have attempted to comprehensively assess the risks associated with the operational safety of water diversion infrastructure by integrating environmental risks, engineering risks, management risks, and social risks. In order to effectively control risks and ensure the safe operation of water diversion infrastructure, there is an urgent need to analyze and prioritize its risks.

In terms of failure mode assessment, Geng *et al.* (2012) calculated the comprehensive risk probability of water delivery channels with the fuzzy analytic hierarchy process (FAHP), and the risk levels of individual water delivery channels with cluster analysis. Hu *et al.* (2013) established a multi-attribute assessment model based on the intuitionistic fuzzy set theory and the technique for order preference by similarity to solution (TOPSIS) method to evaluate social risks during water delivery channel operation. In addition, the fuzzy comprehensive evaluation method and cloud model (Gu *et al.* 2021) have also been widely used in failure mode evaluation research. Experts generally grade failure modes directly as a whole and seldom pay attention to the specific characteristics of each failure mode, such as its probability of occurrence and severity. The failure mode and effects analysis (FMEA) method measures failure mode by evaluating occurrence, severity, and detection difficulty, making it more rigorous and comprehensive.

FMEA is one of the most common methods to analyze system reliability and manage risks in various fields. In traditional FMEA studies, the risk ranking of potential failure modes is confirmed by risk priority number (RPN), i.e., the product of occurrence (O), severity (S), and detection difficulty (D) of a failure mode. However, the traditional FMEA method has the following defects (Li & Cao 2019): (1) The prodect of O, S, and D under different failure modes may generate the same RPN value. Therefore, RPN may not identify high-risk potential failure modes. (2) The fuzziness of risk assessment information in actual application is neglected. (3) The relative importance degree of O, S, and D is neglected. (4) Tiny changes in any risk factor may generate a significant impact on RPN value. (5) The possible dependence among failure modes is neglected.

Some efforts have been made to overcome the drawbacks of the traditional FMEA model. In essence, FMEA has a problem handling multi-attribute decision-making.Therefore, multi-attribute decision-making methods such as *Tomada de decisão interativa multicritério* (TODIM) (Song *et al.* 2013), *vlsekriterijumska optimizacija i kompromisno resenje* (VIKOR) (Liu *et al.* 2015; Li *et al.* 2022), and analytic hierarchy process (AHP) (Ilangkumaran *et al.* 2014) have been applied to improve the FMEA model. In FMEA procedures, fuzzy logic-based methods are always adapted to process subjective information in judgment effectively (Fang *et al.* 2020). Li *et al.* (2022) used fuzzy trigonometric function to evaluate the O, S and D of each failure mode of the South-to-North Water transfer project, which solved the problem that experts could not score accurately, and the effect was remarkable. This idea was extended in this paper.At the same time, this paper employs the fuzzy inference system (FIS) method to improve the traditional FMEA model. On the one hand, this improved model retains the advantages of the traditional FMEA method: evaluating failure mode from the perspective of O, S, and D, which increases the reliability of assessment. On the other hand, the FIS-based FMEA method uses fuzzy thinking to solve the shortcomings of the traditional FMEA method wherein failure mode information is difficult to be directly represent with real numbers. At the same time,it avoids the arbitrariness of personal subjective judgment and the fuzziness of expert experience and can accurately output RPN, solving the problem in the traditional FMEA method of having the same RPN for different failure modes. This method resolves some of the defects of the traditional FMEA method and improves it effectively.

The remainder of this paper is organized as follows. Section 2 introduces the research methodology: the FIS-based FMEA operation risk assessment method. Section 3 demonstrates the effectiveness of the method via a case study. Section 4 is the discussion. Finally, the theoretical contributions and limitations of this paper are presented in section 5.

2. METHODS

2.1. Operation safety failure modes for water diversion inferastructure

The water delivery channels of diversion infrastructure are vulnerable to environmental factors. Sudden floods from storms may erode channel side slopes and cause internal and external ponding, leading to increased instability of channel slope (Guan *et al.* 2016). Earthquakes, as a geological activity with low frequency but extreme and instantil destructive power, may cause irreversible damage to water diversion projects (Weaver *et al.* 2019; Lu *et al.* 2021). Changing water levels may affect the mechanical properties of channel slope, leading to stress damage (Lee *et al.* 2014). External humidity may cause mechanical changes to the soil in the channel, resulting in slope cracks and landslides (Romero & Jommi 2008). Water speed may generate a series of potential impacts, such as heavily washing the channel lining and creating backwater in certain areas (Xi *et al.* 2019).

The failure modes related to engineering technology are relatively hidden in the structure of water diversion infrastructure. A defect in the foundation is the first important failure mode that should be monitored (Geach *et al.* 2017). Anti-frost properties (Han *et al.* 2018), filling quality (Liu *et al.* 2016), excessive height in the levee crown (Wang *et al.* 2016), and slope protection are closely related to design and construction quality and also highly determinate operation safety. Channel slope failure (Abd-Elaty *et al.* 2019) and abnormal seepage (Kwon & Han 2006) are common factors that may pose risks to the safety of water diversion infrastructure. Material aging occurs throughout the entire project operation process and becomes more evident as operation proceeds (Abid *et al.* 2018).

Operation management relies heavily on human behavior. Routine maintenance, such as tour inspections, equipment maintenance (Jiang 2008), and quality maintenance, plays an essential role in operation safety and safety monitoring. The operation schedule is a main aspect of water diversion infrastructure, involving the coordination and management of multiple parties. It proposes higher requirements for normative operation and the timely dissemination of information.

Moreover, many social risk factors derive from various human social activities. After water diversion infrastructure is constructed, inhabitants and management departments will likely have some disputes over water rights (Janjua & Hassan 2020). The level of environmental awareness of nearby residents can affect the safety of the infrastructure (Kedzior 2017). A traffic accident on a cross-channel bridge, particularly when hazardous goods transportation is involved, will affect water quality safety (Elvik *et al.* 2019). As a large-scale project, water diversion infrastructure is vulnerable to human-made damage, and terrorist or dangerous activities should be prevented at all times. Emergency management capacity plays a critical role in guaranteeing the stable operation of the project (Fertier *et al.* 2020).

By systematically and comprehensively analyzing risk factors in the operation process, this study develops a failure mode diagram for water diversion infrastructure, as shown in Figure 1.

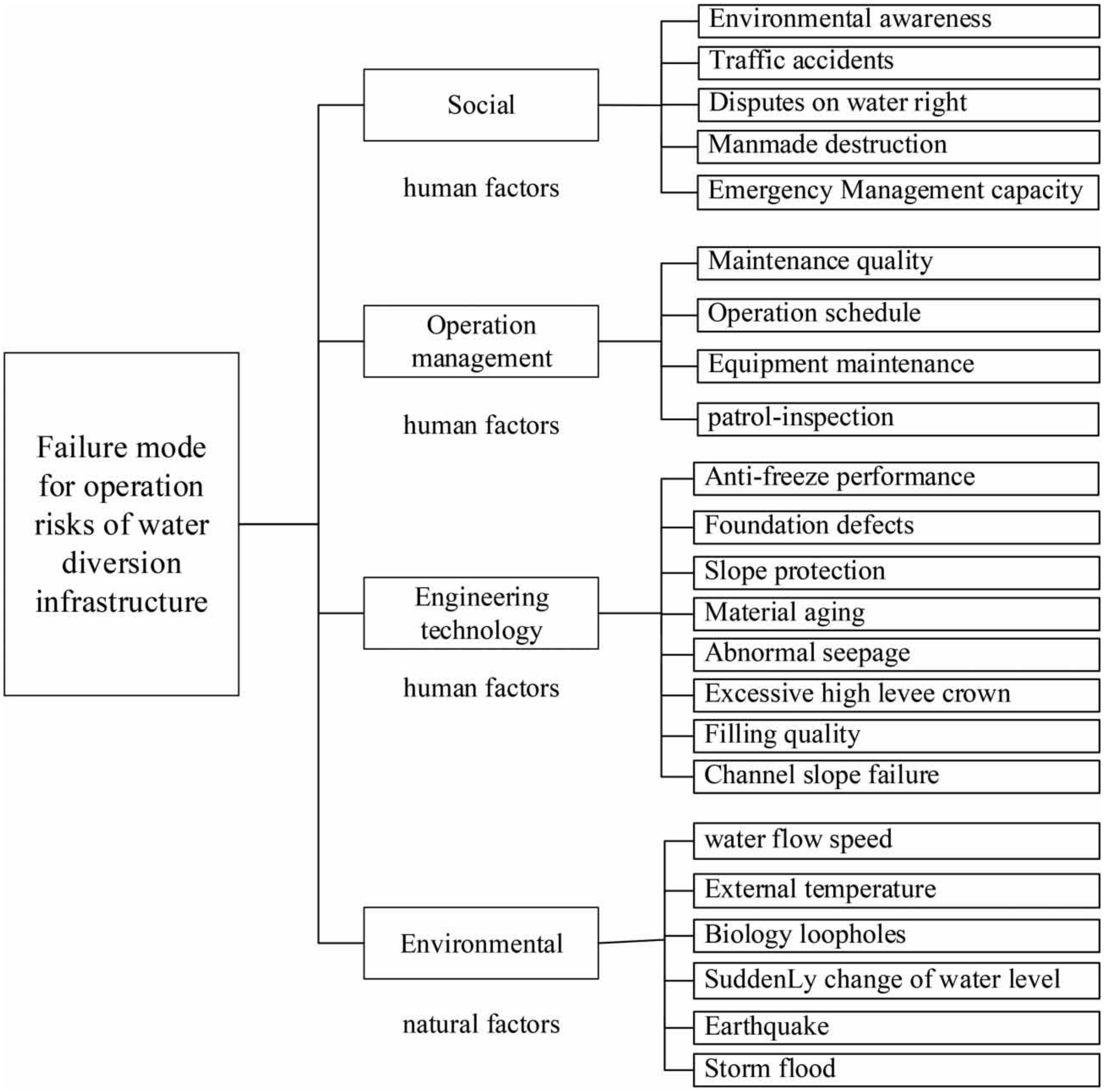


Figure 1 | Failure mode for operation risks of water diversion infrastructure.

2.2. The basis for building the models

2.2.1. Fuzzy expression

To solve the problem of experts being unable to accurately score failure modes, this model applies the concept of fuzziness to experts' evaluations of those modes. The fuzzy expressions of this paper are as follows:

(1) Fuzzy expression of risk factors

In terms of establishing the fuzzy comment set for risk factors, every variable (O, S, and D) is assessed by a score ranging from 1 to 10 points. The scores correspond to five levels of assessment terms, which are assigned triangular fuzzy numbers. The very low (R) level contains the fuzzy number (0, 0, 2.5). The low (L) level contains the fuzzy number (0, 2.5, 5). Medium (M) contains the fuzzy number (2.5, 5, 7.5). High (H) contains the fuzzy number (7, 7.5, 10). Very high (VH) contains the fuzzy number (7.5, 10, 10). For the convenience of examination, an explanation of the three factors (O, S, and D) is shown in Table 1.

Table 1 | Assessment standards for O, S and D of FMEA

Score	Degree of O	Degree of S	Degree of D	Fuzzy number
9 ~ 10	Occurrence is very high: almost inevitable	Very severe impact is generated	The probability of detecting potential risks through various approaches is very low	(7.5, 10, 10)
7 ~ 8	Occurrence is high: occurring repeatedly	Severe impact is generated	The probability of detecting potential risks through various approaches is low	(5, 7.5, 10)
4 ~ 6	Occurrence is medium: occurring occasionally	Medium impact is generated	The probability of detecting potential risks through various approaches is medium	(2.5, 5, 7.5)
2 ~ 3	Occurrence is low: occurring rarely	Minor impact is generated	The probability of detecting potential risks through various approaches is high	(0, 2.5, 5)
1	Occurrence is very low: It is scarcely possible for it to occur	There is hardly any impact	The probability of detecting potential risks through various approaches is very high	(0, 0, 2.5)

The membership function value is from 0 to 1. The language priority terms of O, S, and D are: very low (R), low (L), medium (M), high (H), and every high (VH). A 10-point system scores the three risk factors. The triangular fuzzy membership curve of the three risk factors can be seen in Figure 2.

(2) Fuzzy expression of risk priority

The output value of the membership function is called ‘risk priority’. This research defines five language priority terms on the output terminal of fuzzy inference, i.e. very low (N), low (Mi), medium (Co), high (Ma), and very high (C), as shown in Table 2. The triangular fuzzy membership function of risk priority is shown in Figure 3.

2.2.2. Rank failure modes based on a fuzzy rule base and FIS

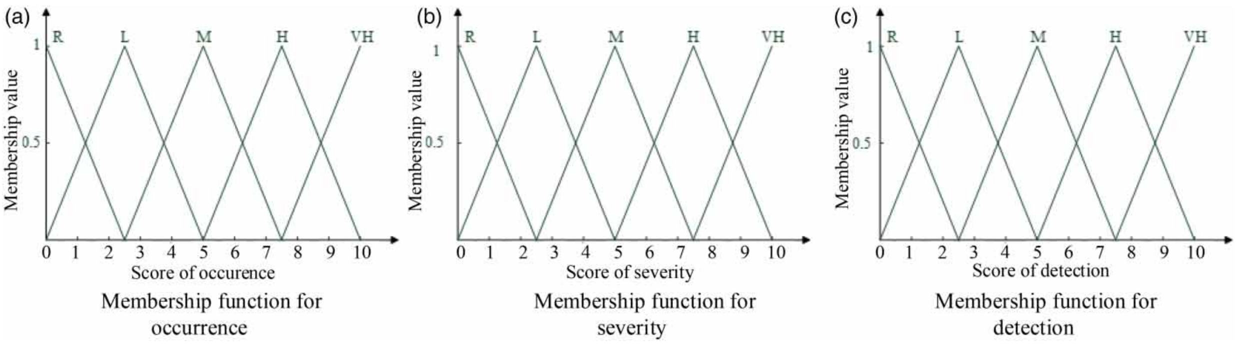
Fuzzy rules are central to fuzzy inference and the essence of fuzzy logic operation. The IF-THEN rule is used to describe the continuous membership function with hypothetical language. Under fuzzy inference with a fuzzy rule base, the hypothetical fuzzy proposition ‘if x is A then y is B’ becomes a fuzzy inference rule. Therefore, a corresponding fuzzy inference conclusion may be acquired through fuzzy inference rules under a given precondition.

The direct inference method of Mamdani (or the MIN-MAX method) is applied to inference based on the fuzzy rule (Mamdani 1974). The Mamdani fuzzy inference algorithm is shown in Formula (1) (Mamdani 1976).

$$\text{R:if } x \text{ is } A \text{ then } y \text{ is } B \tag{1}$$

In Formula (2), x is the input semantic variable; A is a fuzzy set of the inference antecedent; y is the output semantic variable; B is the consequence of the fuzzy rule; and Rc is used to express a fuzzy relationship, as shown below:

$$Rc = A \times B = \int_{X\times Y} \mu_A(x) \wedge \mu_B(y) f(x, y) \tag{2}$$



Membership function for occurrence

Membership function for severity

Membership function for detection

Figure 2 | Fuzzy membership curve of O, S and D.

Table 2 | FMEA risk priority assessment standard

Language priority terms	Explanation	Fuzzy number
C	The priority of the scenario mode is very high	(7.5,8.5,10)
Ma	The priority of the scenario mode is high	(5.5,7,8.5)
Co	The priority of the scenario mode is medium	(3,5,7)
Mi	The priority of the scenario mode is low	(1.5,3,4.5)
N	The priority of the scenario mode is very low	(0,1.5,3)

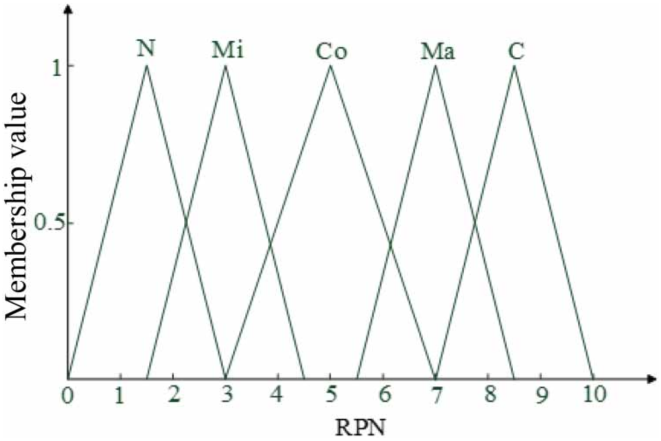


Figure 3 | Fuzzy membership curve of RPN.

When x is A', and the fuzzy relation compositional operation adopts MIN-MAX calculation(Aengchuan & Phruksaphanrat 2018), the calculation of the fuzzy inference is shown in Formula (3).

$$B' = A' \cdot Rc = \int_Y \vee_{x \in X} \{\mu_A(x) \wedge [\mu_A(x) \wedge \mu_B(y)\}/y \tag{3}$$

It should be noted that '$\int$' is not a traditional integral sign but the sum of the corresponding relation of membership and element x in discourse domain X. In Formula (3), $\wedge$ and $\vee$ are fuzzy operators. $\wedge$ means to get the minimum value and $\vee$ means to get the maximum value.

2.3. FIS-based FMEA risk prioritization model

FIS can be divided into four steps: fuzzification, a fuzzy rule base, fuzzy inference, and defuzzification. The process of the FIS-based FMEA model is as follows below and shown in Figure 4.

Step 1: Collect data on the three risk factors (O, S, and D) for each failure mode in Figure 1. Some data is acquired from engineering detection results, and others are collected from expert assessment. The risk assessment level is confirmed for quantitative data according to engineering quality assessment specifications, engineering operation management specifications, and the fuzzy comment set. When engineering detection cannot acquire the data, expert assessment should acquire it. The invited experts will assess risk factors of a given risk failure mode following the assessment standards of O, S, and D described in Table 1. This questionnaire survey divides risk factors O, S, and D into five levels, and scores are drawn according to the 10-point system. The questionnaire consists of three parts. The first part is the explanation of the aims of the questionnaire. The second part collects respondents' background information, including their work organization, work position, and work experience. The third part collects the scores of failure mode risk factors O, S, and D according to experts'

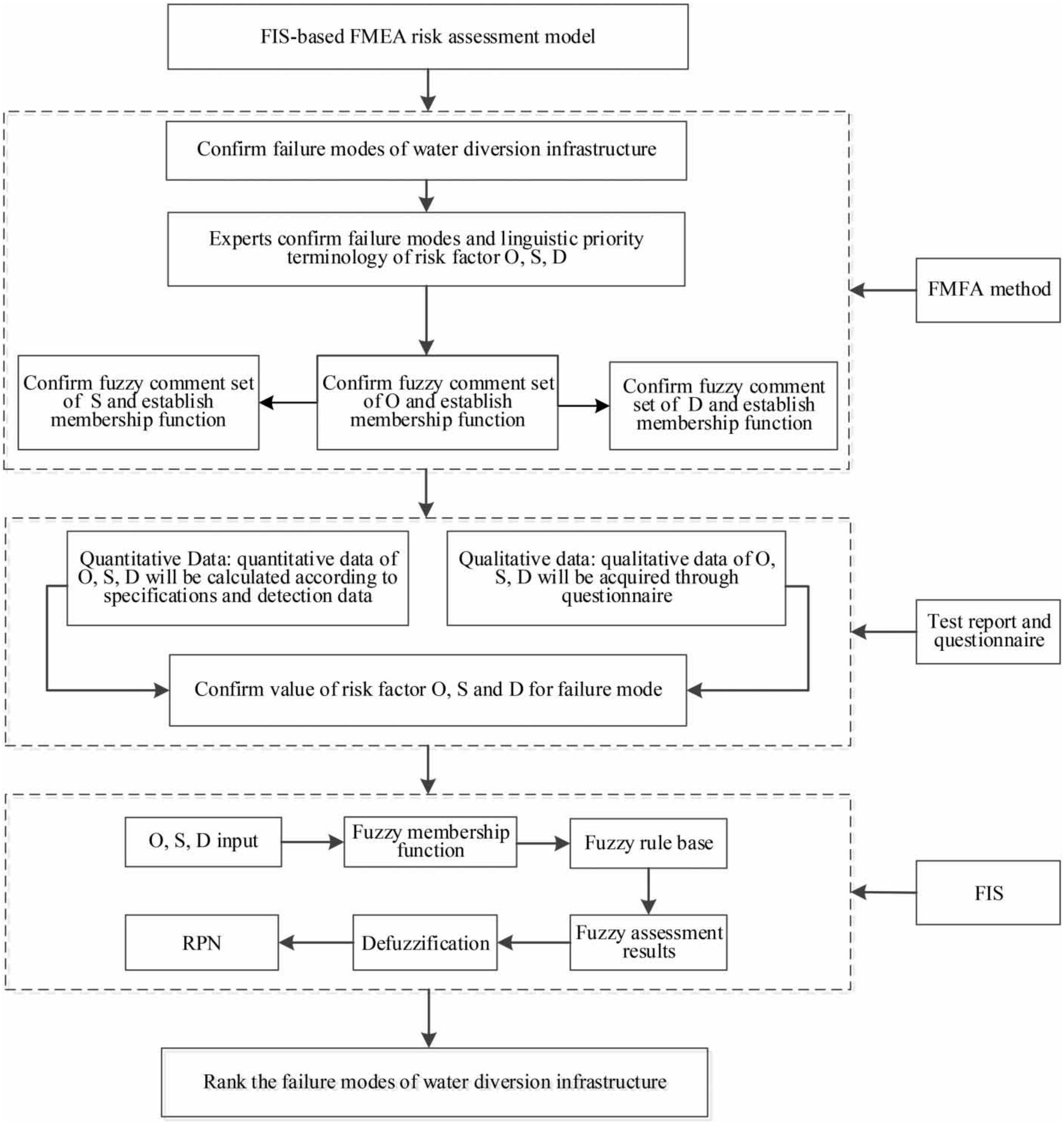


Figure 4 | Framework of FIS-based FMEA for risk prioritization.

experience and perception. The final questionnaire data are collected and analyzed to obtain the O, S, and D scores of the failure modes. Some data of the failure modes can be obtained quantitatively, calculated based on inspection reports.

Step 2: The fuzzification process involves membership functions defining the input/output variable with the linguistic variable. According to the linguistic variable defined by experts' knowledge, five linguistic variables for risk factors O, S, and D are confirmed in this study. The linguistic expression of input/output variables adopts a triangular membership function.

Step 3: The IF-THEN rule is collected from experts to build a fuzzy rule base. In this step, a total of 125 rules are acquired for the FIS-based FMEA method. The standard form of the IF-THEN rule is:

$$\mathrm{R}_i\text{: } if\ x_1\ is\ A_{i1}\ and\ x_2\ is\ A_{i2} \cdots then\ y\ is\ B_i,\ (i = 1, 2, 3, \cdots k)$$

In the formula R_i represents the rule serial number. k represents rule number. x_1, x_2, and$y$ represent two input linguistic variables and one output linguistic variable, respectively.

Step 4: Fuzzy inference, the reasoning process based on the IF-THEN rule, is carried out. The output membership function in Mamdani FIS is a fuzzy set. The conclusion is drawn with fuzzy language.

Step 5: Defuzzification is completed: the RPN drawn from the fuzzy rule is presented according to fuzzy membership. It should be converted into a distinct value through defuzzification to rank the failure modes. The weighted average method is applied to the defuzzification method in fuzzy inference. The calculation is shown in Formula (4).

$$z^* = \frac{\int_a^b zW(z)\mathrm{d}z}{\int_a^b W(z)\mathrm{d}z}, U = [a, b] \tag{4}$$

where, $W(x)$ is the weight function.

We often use the membership value of fuzzy set C on point z as the weight function or weight coefficient. The method can be converted to the gravity method, shown in Formula (5):

$$z^* = \frac{\int_a^b zC(z)\mathrm{d}z}{\int_a^b C(z)\mathrm{d}z}, U = [a, b] \tag{5}$$

The RPN values of each failure mode were determined from the defuzzification of the gravity method. Failure modes would be ranked according to their RPN.

3. CASE STUDY

The Huixian section of the Middle Route Project of the South-to-North Water Diversion Project (MRP-SNWDP) is selected as a case study in this research. The South-to-North Water Diversion Project is a strategic infrastructure in China with the most significant investment scale and most intensive coverage in the world. The MRP-SNWDP diverts water from the Danjiangkou Reservoir of the Han River with an open channel along the central and western edge of the North China Plain; it crosses the Yellow River through a tunnel, moves northward along the western side of the Beijing-Guangzhou Railway, and flows into Tuancheng Lake in the Summer Palace of Beijing. The project passes through Henan Province, Hebei Province, Beijing, and Tianjin. It provides water for the production, living, and agriculture of more than a dozen large and medium-sized cities along the route. The total water supply area is 155,000 square km (Liu *et al.* 2020). The Huixian section of the project is located in the northwest of Henan Province, as shown in Figure 5. The total length of the section is 48.951 km, including 43.631 km with an open water delivery channel and 5.320 km with 78 hydraulic structures. The channel is mainly fully excavated, with excavated sections accounting for 63% of the total length. There is a more deeply excavated section about 15 m deep and 1.5 km long, and the maximum depth is about 32 m. The area has a warm temperate continental monsoon climate type. The annual precipitation changes significantly, with the main rainfall concentrated in summer. The annual average precipitation reaches 589.1 mm, peaking in July, which has up to 182.3 mm of precipitation. We apply the model in this article to specific examples from the Huixian section of the MRP-SNWDP to verify its effectiveness and with the aim of narrowing the gap between practice and academia in construction safety research.

3.1. Data collection and analysis

Risk assessment experts were asked to evaluate failure modes from the perspectives of environment, engineering technology, operation management, and society. The engineering technology data includes quantitative data and qualitative data. The quantitative data are filling quality and material aging. For the failure modes of filling quality and material aging, the score for S is calculated based on data in the inspection report for channels in the Huixian section. The questionnaire survey is carried out to determine the scores for D and O. The rest of the failure mode evaluation data are from the questionnaire survey. The details of the questionnaire are shown in the appendix.

A total of 24 people were invited to fill out the questionnaire, including 12 from the operation department of water diversion infrastructure, 5 from research institutions, and 7 from construction companies, as shown in Table 3 below. The questionnaire recovery rate was 100%.

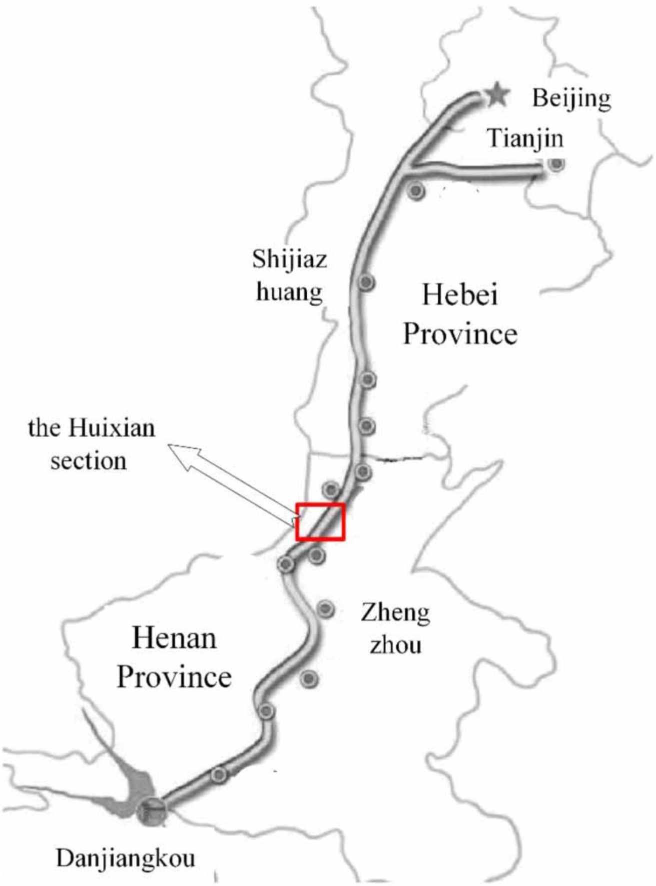


Figure 5 | Location of the Huixian section of the MRP-SNWDP (Nie *et al.* 2019).

Table 3 | Profiles of experts

Background	**Sample level**	**Frequency**	**Percentage**
Types of organization	Operation department of water diversion infrastructure	12	50%
	Research institute	5	20.8%
	Construction company	7	29.2%
Work experience	0–2 years	0	0%
	3–5 years	4	16.7%
	6–10 years	8	33.3%
	11–20 years	10	41.7%
	Over 20 years	2	8.3%

To ensure the reliability of the questionnaire results and reduce the bias in the questionnaire, all the respondents were selected experts who had more than three years of work experience and rich knowledge of water diversion infrastructure construction. At the same time, the reliability and validity of the questionnaire results were tested. The questionnaire data were input into SPSS 23.0 software, and Cronbach's α and KMO were calculated to test the reliability and validity.The Cronbach's α and KMO of the questionnaire are 0.85(>0.8) and 0.78(>0.7), respectively, indicating that the reliability and validity can be accepted.

Different weights will be assigned to experts when processing questionnaire data according to their experience. The weight allocation should be 0.1 for 3–5 years, 0.2 for 6–10 years, 0.3 for 11–20 years, and 0.4 for over 20 years. Each experts' scores for O, S, and D are obtained from Formula (6).

$$\mathrm{X}_{\mathrm{i,O,S,D}} = \mathrm{x}_{\mathrm{i}} \times W_{\mathrm{i}} \tag{6}$$

x_i refers to the value directly from the questionnaire, and W_i refers to the weight of each expert's for judgment. The final values of O, S, and D are obtained from Formula (7).

$$S_{O,S,D} = \sum_{i=1}^{n} \frac{X_{i,O,S,D}}{n} \tag{7}$$

$S_{O,S,D}$ refers to the final weighted value of O, S, and D from the questionnaire. n refers to the number of respondents. The final values of O, S, and D are shown in Table 4.

3.2. Risk assessment process

Step 1: Fuzzification

In this paper, the traditional FMEA method is improved based on the principle of fuzzy mathematics. Risk factors O, S and, D are divided into five levels: very low (R), low (L), medium (M), high (H), and very high (VH). The membership degree of risk factors to R, L, M, H, and VH is acquired according to Formula (8).

$$\begin{cases} f(x) = -\frac{2}{5}x + 1 \quad & 0 \le x \le 2.5 \quad \text{VL} \\ f(x) = \begin{cases} \frac{2}{5}x & 0 \le x \le 2.5 \\ -\frac{2}{5}x + 2 & 2.5 \le x \le 5 \end{cases} & \text{L} \\ f(x) = \begin{cases} \frac{2}{5}x - 1 & 2.5 \le x \le 5 \\ -\frac{2}{5}x + 3 & 5 \le x \le 7.5 \end{cases} & \text{M} \\ f(x) = \begin{cases} \frac{2}{5}x - 2 & 5 \le x \le 7.5 \\ -\frac{2}{5}x + 4 & 7.5 \le x \le 10 \end{cases} & \text{H} \\ f(x) = \frac{2}{5}x - 3 \quad & 7.5 \le x \le 10 \quad \text{VH} \end{cases} \tag{8}$$

Table 4 | Risk factor value for every failure mode

Failure Mode Type	Failure Mode	O	S	D
Environmental	Storm flood	6.2	9.1	3.7
	Earthquake	1.3	7.9	6.2
	Sudden change of water level	3.4	7.1	2.9
	Biological loopholes	3.3	4.8	4.9
	External temperature	2.8	5.1	2.4
	Water flow speed	3.2	5.5	2.1
Engineering technology	Channel slope failure	3.7	8.1	2.4
	Filling quality	4.1	6.3	5.2
	Excessively high levee crown	1.8	5.7	2.1
	Abnormal seepage	4.3	8.1	3.2
	Material aging	3.6	2.3	4.2
	Slope protection	4.6	2.8	3.1
	Foundation defects	5.2	7.1	5.1
	Anti-freeze performance	3.2	5.4	4.7
Operation management	Tour inspection	3.1	4.2	3.8
	Equipment maintenance	7.1	3.4	2.9
	Operation schedule	2.8	6.7	2.2
	Maintenance quality	5.1	3.4	2.2
Social	Emergency management capacity	2.9	6.1	2.6
	Manmade destruction	3.5	5.7	2.2
	Disputes on water rights	1.2	4.6	1.8
	Traffic accidents	2.1	6.3	1.8
	Environmental awareness	3.3	5.2	4.1

Five language priority terms are defined for the output of fuzzy inference, i.e. very low (N), low (Mi), medium (Co), high (Ma), and very high (C). The membership degree of risk factors to N, Mi, Co, Ma and C is acquired according to Formula (9).

$$\begin{cases} f(x)=\begin{cases} \frac{2}{3}x & 0 \le x \le 1.5 \\ 2-\frac{2}{3}x & 1.5 \le x \le 3 \end{cases} \\ f(x)=\begin{cases} \frac{2}{3}x-1 & 1.5 \le x \le 3 \\ 3-\frac{2}{3}x & 3 \le x \le 4.5 \end{cases} \\ f(x)=\begin{cases} \frac{1}{2}x-\frac{3}{2} & 3 \le x \le 5 \\ \frac{7}{2}-\frac{1}{2}x & 5 \le x \le 7 \end{cases} \\ f(x)=\begin{cases} \frac{2}{3}x-\frac{11}{3} & 5.5 \le x \le 7 \\ \frac{17}{3}-\frac{2}{3}x & 7 \le x \le 8.5 \end{cases} \\ f(x)=\begin{cases} \frac{2}{3}x-\frac{14}{3} & 7 \le x \le 8.5 \\ \frac{20}{3}-\frac{2}{3}x & 8.5 \le x \le 10 \end{cases} \end{cases} \tag{9}$$

Step 2: Establishing a fuzzy rule base

The following two methods are often used to confirm fuzzy rules: (1) Fuzzy rules based on knowledge and experience of experts; (2) fuzzy rules based on sample data. Since relevant statistical data is lacking, and each layer of FIS involves only a few variables and fuzzy number sets, the fuzzy rules are confirmed based on experts' knowledge and experience in this study.

Risk priority is defined in the proposed fuzzy rule base, which is the output value of the membership functions of the three risk factors (O, S, and D). The total number of fuzzy rules in this research is 125 ($5 \times 5 \times 5$), and the specific rule base is shown in Table 5.

Step 3: Risk assessment

In this section, we take foundation defects as an example.

The minimum value of the three membership degrees under the different risk levels for foundation defects is obtained through FIS. According to Formula (9), the eight combinations of membership value are as follows:

Foundation defects is found to belong to the two risk levels of Co and Ma. Then, the maximum value of the membership degree of foundation defects under these different levels is confirmed:

$$Co = \max(0.16, 0.04, 0.08) = 0.16$$

$$Ma = \max(0.84, 0.04, 0.08, 0.04, 0.04) = 0.84$$

According to the membership function in Figure 3 and defuzzification in Formula (5), the output fuzzy RPN = 6.45.

According to the steps mentioned above, the fuzzy RPN of every failure mode can be obtained.

3.3. Result

The Mamdani FIS of fuzzy RPN is established in the Matlab fuzzy toolbox. The score values of risk factors (O, S, and D) are inputted into the FIS model. The membership curves of risk factors O, S and D in Figure 2, the membership curves of fuzzy RPN in Figure 3, and the fuzzy rules in Table 5 were input into Matlab to obtain the corresponding relationship between the score of risk factors O, S and D and the level of RPN, as shown in Figure 6. Figure 6(a)–6(c) represent any two corresponding surfaces of O,S and D with RNP level. It is easy to see that the spatial surface map is smooth, the surface output is nearly continuous, and there is no abnormal bulge or no output, which indicates that the fuzzy rules are reasonable and the output results are effective. Figure 6(d) shows the relationship between the score of O, S, D and RPN level. Enter the

Table 5 | FMEA fuzzy rule base

		Severity (S)				
Detection difficulty (D)	**Occurrence (O)**	**R**	**L**	**M**	**H**	**VH**
R	R	N	N	N	N	Mi
	L	N	N	N	Mi	Mi
	M	N	N	Mi	Mi	Mi
	H	Mi	Mi	Mi	Co	Co
	VH	Mi	Mi	Co	Ma	Ma
L	R	N	N	N	Mi	Mi
	L	N	N	N	Mi	Co
	M	N	Mi	Co	Co	Ma
	H	Mi	Co	Co	Ma	Ma
	VH	Mi	Co	Ma	C	C
M	R	N	N	Mi	Mi	Co
	L	N	Mi	Mi	Co	Ma
	M	Mi	Mi	Co	Ma	Ma
	H	Mi	Co	Co	Ma	C
	VH	Mi	Co	Ma	C	C
H	R	N	N	Mi	Mi	Co
	L	N	Mi	Mi	Co	Ma
	M	Mi	Mi	Co	Ma	C
	H	Mi	Co	Ma	Ma	C
	VH	Co	Ma	Ma	C	C
VH	R	N	N	Mi	Co	Ma
	L	N	Mi	Co	Co	Ma
	M	Mi	Co	Ma	Ma	C
	H	Co	Ma	Ma	C	C
	VH	Ma	Ma	C	C	C

If O = 0. 92(M), S = 0.16(M), D = 0. 96(M), then ‘fuzzy RPN’ = Co.
If O = 0. 92(M), S = 0. 84(H), D = 0. 96(M), then ‘fuzzy RPN’ = Ma.
If O = 0. 92(M), S = 0.16(M), D = 0.04(H), then ‘fuzzy RPN’ = Co.
If O = 0. 92(M), S = 0. 84(H), D = 0.04(H), then ‘fuzzy RPN’ = Ma.
If O = 0.08(H), S = 0.16(M), D = 0. 96(M), then ‘fuzzy RPN’ = Co.
If O = 0.08(H), S = 0. 84(H), D = 0. 96(M), then ‘fuzzy RPN’ = Ma.
If O = 0.08(H), S = 0.16(M), D = 0.04(H), then ‘fuzzy RPN’ = Ma.
If O = 0.08(H), S = 0. 84(H), D = 0.04(H), then ‘fuzzy RPN’ = Ma.

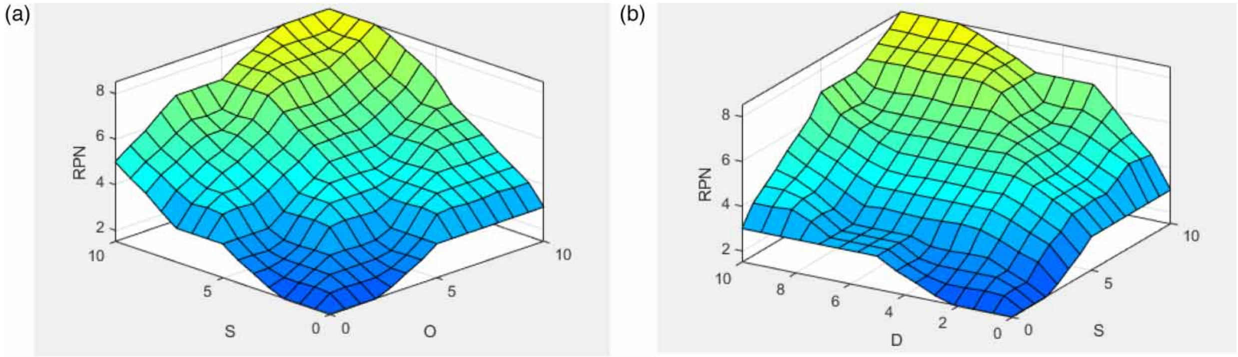
score of risk factors O, S, and D in this view interface to obtain the corresponding RPN result.The final results of RPN and the prioritization of the failure modes are as shown in Table 6. To compare the difference between results obtained by this method and the traditional FMEA method, the final RPN results and the prioritization of the failure modes of the traditional FMEA are also shown in Table 6.

Table 6 clearly show the RPN score of each failure mode and the final failure mode ranking as determined by the improved model. Meanwhile, traditional FMEA results can be compared. The model in this paper is used to evaluate the operation safety failure modes of the Huixian section of MRP-SNWDP, and the top six operation safety failure modes are as follows: storm flood, foundation defects, filling quality, abnormal seepage, equipment maintenance, and slope failure. The top six failure modes obtained by the traditional FMEA method are the following: storm flood, foundation defects, filling quality, abnormal seepage, anti-freeze performance, and biological loopholes. Specific analysis and comparison of results are presented in the following section.

4. DISCUSSION

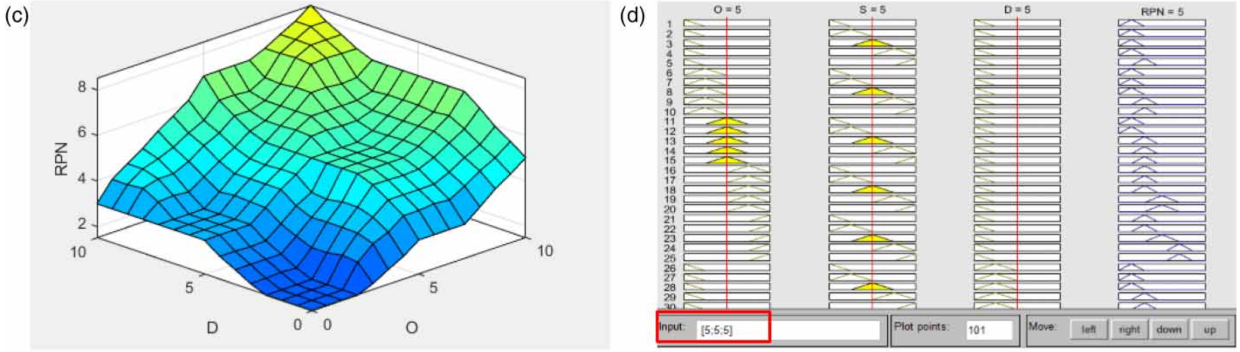
4.1. Interpretation of result

According to Table 6, the storm flood risk failure mode is ranked first. The Huixian section of the MRP-SNWDP is close to the western portion of the Taihang Mountains. The terrain declines in steps from the northwest to the southeast and has a



Curved surface of the relationship between O, S and RPN levels

Curved surface of the relationship between D, S and RPN levels



Curved surface of the relationship between D, O and RPN levels

Relationship between O, S, D scores and RPN levels

Figure 6 | Graph of the relationship between O, S, D, and RPN levels.

large slope. The rainfall catchment is forming rapidly. Once the flooding of crossed rivers overflows the drainage aqueduct or discharge capacity of the inverted siphon, the water will remain in the left river bank. Therefore, water seepage will threaten the safety of the channel. Meanwhile, flood washing and debris could cause collapse and landslides along the channel embankment. The experts have assigned 9.1 points to the severity of a storm flood. The judgment of experts is consistent with reality. Moreover, there are over 10 precipitation stations on the left side of the main channel, the observation periods of which are more than 40 years. The hydrological computation can be carried out according to the hydrological computation atlas of Henan Province. A storm flood is easy to forecast in some instances. Therefore, the 3.7 points assigned by experts for the detection difficulty of flooding is also consistent with reality.

The foundation defect risk failure mode ranks in second place. The channel in the Huixian section is 43.63 km long, and about 75.29% of the channel section has loess-like soil. The foundation is mostly in collapsible loess with a collapse depth between 5 and 8 m and an even worse anti-erosion ability. The strength of the foundation will deteriorate when it contacts water. During the construction period, cushion replacement and dynamic consolidation methods were carried out to strengthen the foundation. However, during the operation period, the load increased, and slope ponding, channel seepage, and rising underground water levels should be heeded to prevent slope disability and channel siltation.

The filling quality risk failure mode ranks third. The channel was excavated from the top down in layers during the construction period. Some over-excavation and under-excavation problems were not handled in time because of the long construction route, complex strati graphic texture along the route, and different technology levels of the constructors. Some filling soil has a large plastic index, high clay particle content, and weak expansibility, affecting filling quality during complete cross-section construction. The inspection reports have shown that some earthwork soil filling areas are unqualified, and some soil layers lack pressure. The treatment of the foundation is concealed work. After continuous soaking by external and internal water during operation, any areas completed using shortcuts may become unstable and directly affect channel operation safety.

Table 6 | Comparison of failure mode ranking

Failure mode	RPN	Ranking	Traditional RPN	Ranking
Storm flood	6.72	1	208.75	1
Earthquake	4.55	7	63.67	11
Sudden change of water level	4.03	8	70.01	9
Biology loopholes	3.82	10	77.62	6
External temperature	2.32	20	34.27	20
Water flow speed	2.94	16	36.96	18
Channel slope failure	4.64	6	71.93	7
Filling quality	5.18	3	134.32	3
Excessive high levee crown	1.98	22	21.55	22
Abnormal seepage	5	4	111.46	4
Material aging	2.43	19	34.78	19
Slope protection	3.14	14	39.93	16
Foundation defects	6.45	2	188.29	2
Anti-freeze performance	3.98	9	81.22	5
Tour inspection	3.05	15	49.48	12
Equipment maintenance	4.68	5	70.01	9
Operation schedule	2.91	17	41.27	15
Maintenance quality	3.73	11	38.15	17
Emergency management capacity	2.9	18	45.99	13
Manmade destruction	3.25	13	43.89	14
Disputes on water right	1.5	23	9.94	23
Traffic accidents	2.27	21	23.81	21
Environmental awareness	3.52	12	70.36	8

The abnormal seepage risk failure mode is fourth. The main patterns of abnormal seepage are piping, flowing soil, concentrated leakage, and soaking out. Serious piping may lead to local depression, deformation, and even collapse of the channel. Flowing soil may cause slope softening or instability. The hazards caused by concentrated leakage are similar to those of piping, but they develop faster. Soaking out may lead to slope toe softening, low slope stability, and local instability. The experts scored abnormal seepage as 8.1 in severity. An osmometer has been embedded into the channel to monitor the change of seepage pressure directly. So, the experts scored the detection difficulty as 3.2. Both the severity and detection difficulty scores are consistent with reality.

The equipment maintenance risk failure mode ranks fifth. Here, equipment mainly refers to metal structures, start/stop devices, and the power supply system. There are 14 sets of equipment with metal structures in the Huixian section, including the gate slot, sluice gate, gate hoist, and embedded parts. There are 15 sets of power supply equipment, mainly including the operating gate, overhaul gate, indoor and outdoor lighting, repair facilities, and automatic control devices. The accidental failure of the metal structure, hoisting devices, and the power supply system may directly affect the whole route water schedule, gate openness, and safety inspection of the water channels. Mechanical equipment failures are routinely detected during scheduled and unannounced inspections. The experts have given equipment maintenance failure a score of 7.1 points for occurrence and 3.4 points for severity. The ‘Maintenance and Repair Rules for Metal Structure and Mechanical Equipment MRP-SNWDP’ regulates tour inspection content and frequency, standards of equipment, specific parameters for maintenance and repair, and the criteria for meeting tour inspection demands for equipment maintenance. Thus, experts scored detection difficulty as a 2.9. The occurrence, severity, and detection difficulty are consistent with reality.

The slope failure risk failure mode ranks sixth. The causes of slope failure risk are divided into basic conditions and external conditions. The basic conditions mainly depend on landform and geological conditions. The lower the bearing ability of the foundation soil layer, the more likely channel slope failure will occur. The external conditions include sudden water level change caused by earthquakes, storms, and floods, which change the original stress status of the channel slope and cause instability and accidents. Only 63% of the total length of the Huixian section is fully excavated, and the remaining 37% is half-excavated. Slope failure will not only affect the water delivery safety of the entire route, but it will also cause overflow of the embankment and regional flooding around the channels. Therefore, the consequences and losses due to slope failure are vast. Experts scored slope failure as an 8.1 for severity. Slope failure occurs after a deformation stage and destruction stage. Slope failure thus takes a long time to accumulate, so the occurrence is low. The experts scored the occurrence as 3.7 points. Slope failure can be easily detected in time through routine tour inspections. The experts' score for detection difficulty, 2.4 points, is consistent with reality.

4.2. Model validity analysis

The model in this paper is used to evaluate the operation safety failure modes of the Huixian section of the MRP-SNWDP, and the top six operation safety failure modes are as follows: storm flood, foundation defects, filling quality, abnormal seepage, equipment maintenance, and slope failure. Wang *et al.* (2021) evaluated the operation risks of the Henan section of the MRP-SNWDP and concluded that geological conditions had the highest risk grade with construction quality ranked second highest. Nie *et al.* (2022) adopted risk entropy and accident system risk transfer theory to conclude that flood disasters will have a significant impact on MRP-SNWDP. These findings are consistent with the results of this study. At the same time, field investigations demonstrate that the model is consistent with actual engineering projects in reality, which proves the validity of the model.

To further explain the effectiveness of the proposed model, the failure mode ranking results are compared with the calculation results of RPN in traditional FMEA, as shown in Table 6. The comparison results can be summarized as follows:

(1) Different combinations of O, S, and D may generate the same RPN value precisely, but the risk connotations may be completely different. For example, the O and S scores for the sudden change of water level and equipment maintenance are inconsistent, but the calculation results of traditional FMEA give them the same risk priority. It is challenging to confirm the risk priority of these two failure modes in the traditional model. The proposed method, however, can make a clean risk priority ranking.

(2) On the other hand, the two methods' risk priority results are very similar. The risk priority of 15 failure modes is close, and nine failure modes are precisely the same. The risks of storm flood and foundation defects are still the largest, while excessively high levee crowns and water rights disputes are the most negligible risks. Yet our method improves the reliability of risk priority results by using triangular fuzzy number processing and analysis to effectively solve the problem of the uncertainty and fuzziness of the information upon which risk priority is determined.

(3) The earthquake failure mode was ranked seventh based on the proposed method. However, according to traditional FMEA, its ranking is eleventh. That is because the frequency of earthquakes is low, but the detection difficulty (D) and severity (S) are high. When an earthquake occurs, its consequences are very severe. Thus, its risk ranking should be relatively high despite its relative infrequency. This study obtains the RPN value of failure modes like earthquakes using FIS. FIS is based on fuzzy rules that can deal with uncertain and fuzzy linguistic concepts. Because FIS is based on fuzzy logic, it effectively integrates intelligent decisions and typical mathematical methods to reflect human beings' thinking more accurately. It is a powerful way to describe and process proximate, inaccurate, and uncertain problems in reality.

Water diversion infrastructure has multiple risk factors and failure has severe consequences. In this paper, the FIS-based FMEA model is used to assess the operation failure modes of water diversion infrastructure. Although this model improves the traditional FMEA method effectively, it also has certain disadvantages: the scores of O, S, and D still depend on experts' scoring, so there is subjective uncertainty. The number of questionnaires collected in this study was small. Further research is needed on the selection of experts.

5. CONCLUSION

The FIS-based FMEA method proposed in this paper is applied to the risk assessment of the Huixian section of the MRP-SNWDP. It is concluded that the top six operation safety failure modes are: storm flood, foundation defects, filling quality, abnormal seepage, equipment maintenance, and slope failure.

Storm flood is an environmental risk. The Huixian section of the MRP-SNWDP is prone to heavy rains and frequent floods, which pose a great threat to the safe operation of the project. The management personnel should always pay attention to the water level of the river, rainfall intensity and other information, grasp the possible flood situation along the route, achieve flood control linkage, and formulate scientific management measures. Foundation defects, filling quality, abnormal seepage, and slope failure are engineering technical risks. The foundation of the MRP-SNWDP is generally soil foundation. During the construction of the project, the foundation that does not meet the requirements of bearing capacity has been treated, but due to the time difference of channel filling, the difference of compaction degree is too large, it is easy to appear abnormal seepage, slope instability and other phenomena. The uneven settlement of foundation should be monitored in real time, and the undesirable geological sections such as expansive soil and collapsible loess should be replaced. Focus on inspection whether there are cracks, collapse, serious uneven settlement, non-convergent tilt and horizontal displacement, abnormal leakage, and other phenomena, timely treatment reduces the risk. Equipment maintenance is an operation management risk. Operation and dispatching personnel should patrol the operation of the system in strict accordance with the management system, analyze the water situation and work situation data, and report any abnormality immediately. Engineering inspection should be carried out responsibilities, timely maintenance of equipment, truthfully record the process of inspection, timely report the abnormal situation, and timely maintenance of facilities found damaged.

Risk prevention reflects the achievement of risk identification and is the key step of risk management. Risk identification aims to identify the risks that are easy to occur, formulate emergency plans, take various measures and methods to reduce the risks in the operation of the project, and minimize the loss after the risk occurs. The fundamental purpose of risk identification can be realized only when risk prevention is implemented. Water diversion infrastructure entails difficult technology and complex engineering, and many factors affect its operation. It is therefore extremely important to identify and prevent operation safety failure modes.

As a very important safety and reliability analysis tool, FMEA has been widely used in risk management. In FMEA, potential failures are identified and can be assessed by the O, S, and D of failure modes. Risk assessment in FMEA is carried out by developing a risk priority number, which is determined by finding the multiplication of risk factor scores. Although there are many attractions, but in practical applications, FMEA risk assessment is often affected by uncertainty, fuzzy set theory is a suitable tool to solve this kind of problem. FIS is a system inference process that uses fuzzy logic to form input/output mappings. The fuzzy input values of S, O, and D are output to clear values by fuzzy rules, which slows down the high sensitivity of scalar multiplication to multipliers. Therefore, the risk assessment method of FIS-based FMEA is established in this paper.

This paper adopts four dimensions of failure modes in water diversion infrastructure operation: environmental risk, engineering risk, management risk, and social risk. The scores were quantified by questionnaire surveys and fuzzy logic. The FIS-based FMEA method was used to assess the operational failure modes. This research process has wide applicability, as the research framework can be effectively applied to risk analysis of other infrastructure projects. The theoretical contributions of this paper are as follows:

(1) The operational safety failure modes of water diversion infrastructure are identified from the four dimensions of environment, engineering technology, operation management, and society. This provides a valuable research route for risk assessment of large-scale water diversion projects. Identify failure modes from three aspects of O, S, and D, which increases the reliability of evaluation results.
(2) A risk prioritization framework is developed using the FIS-based FMEA method. Fuzzy logic is used to rank failure mode to avoid RPN repetition. The fuzzy rule base determines a nonlinear causal relationship between FMEA risk factors and has a higher sensitivity to risk ranking results. It can discover potential failure modes more effectively to highlight essential and hidden risks.
(3) Using triangle fuzzy number instead of clear number is helpful to transform expert cognitive information more accurately and describe the diversity and uncertainty of evaluation information better.

Although the proposed method in this study has been proven feasible, it still has some weaknesses. The most notable limitation is the subjectivity of the questionnaire survey in the study. Data from questionnaires are dependent on the knowledge and experience of experts. Although all the survey respondents are familiar with water diversion infrastructure, future studies could invite more experts in this field to participate in subsequent surveys and collect accurate data from those in operational management. Additionally, the study only obtained the order of each operational safety failure mode, but did not get an accurate score. These problems need to be constantly considered and improved. This paper scores O, S, and D according to the standard documents for quantitative indicators and the questionnaire survey for qualitative indicators. In the future, big data, machine learning, text mining, and other methods can be used to obtain O, S, and D scores for failure modes from historical data so as to enhance the objectivity of the O, S, and D scores. At the same time, this paper only considers the operation safety failure modes for water diversion infrastructure, and future research can consider the risks faced by water diversion structures during their whole life cycle.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abd-Elaty, I., Eldeeb, H., Vranayova, Z. & Zelenakova, M. 2019 Stability of irrigation canal slopes considering the sea level rise and dynamic changes: case study El-Salam Canal, Egypt. *Water* **11** (19). https://doi.org/10.3390/w11051046.

Abid, S. R., Hilo, A. N. & Daek, Y. H. 2018 Experimental tests on the underwater abrasion of engineered cementitious composites. *Construction and Building Materials* **171**, 779–792. https://doi.org/10.1016/j.conbuildmat.2018.03.213.

Adeniran, A., Daniell, K. A. & Pittock, J. 2021 Water infrastructure development in Nigeria: trend, size, and purpose. *Water* **13**. https://doi.org/10.3390/w13172416.

Aengchuan, P. & Phruksaphanrat, B. 2018 Comparison of fuzzy inference system (FIS), FIS with artificial neural networks (FIS plus ANN) and FIS with adaptive neuro-fuzzy inference system (FIS plus ANFIS) for inventory control. *Journal of Intelligent Manufacturing* **29**, 905–923. https://doi.org/10.1007/s10845-015-1146-1.

Elvik, R., Sagberg, F. & Langeland, P. A. 2019 An analysis of factors influencing accidents on road bridges in Norway. *Accident Analysis and Prevention* **129**, 1–6. https://doi.org/10.1016/j.aap.2019.05.002.

Fang, H., Li, J. & Song, W. Y. 2020 Failure mode and effects analysis: an integrated approach based on rough set theory and prospect theory. *Soft Computing* **24** (9), 6673–6685. https://doi.org/10.1007/s00500-019-04305-8.

Fertier, A., Barthe-Delanoe, A. M., Montarnal, A., Truptil, S. & Benaben, F. 2020 A new emergency decision support system: the automatic interpretation and contextualisation of events to model a crisis situation in real-time. *Decision Support System* **133** (11). https://doi.org/10.1016/j.dss.2020.113260.

Geach, M. R., Stokes, M. & Hart, A. 2017 The application of geomorphic indices in terrain analysis for ground engineering practice. *Engineering Geology* **217**, 122–140. https://doi.org/10.1016/j.enggeo.2016.12.019.

Geng, L. H., Jiang, B. L., Fu, K. W. & Mao, Y. J. 2012 Risk analysis and assessment of the water conveyance system operation in the east route of South-to-North water transfer project. *Yellow River* **34**, 92–95.

Gu, L., Zhang, C. & Wu, T. 2021 Financing risk assessment of major water conservancy PPP projects based on cloud model. *Yellow River* **43**, 116–121.

Guan, M. F., Carrivick, J. L., Wright, N. G., Sleigh, P. A. & Staines, K. E. H. 2016 Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. *Journal of Hydrol* **538**, 256–268. https://doi.org/10.1016/j.jhydrol.2016.04.004.

Han, X., An, X. H. & Liu, C. N. 2018 Integrated risk evaluation of large river-crossing buildings in the middle of the South-to-North water diversion project. *Journal of Tsinghua University(Science and Technology)* **2018** (07), 639–649. https://doi.org/10.16511/j.cnki.qhdxxb.2018.25.030.

He, Z., Huang, D., Zhang, C. & Fang, J. 2018 Toward a stakeholder perspective on social stability risk of large hydraulic engineering projects in China: a social network analysis. *Sustainability* **10**. https://doi.org/10.3390/su10041223.

Hu, D., Zheng, L., Li, S. & Shi, G. K. 2013 Study on the risk evaluation method for the open channel operation in the middle route of South-to-North water diversion project. *South-to-North Water Transfers and Water Science & Technology* **11**, 98–101.

Ilangkumaran, M., Shanmugam, P., Sakthivel, G. & Visagavel, K. 2014 Failure mode and effect analysis using fuzzy analytic hierarchy process. *International Journal of Productivity and Quality Management* **4**, 296–313. https://doi.org/10.1504/ijpqm.2014.064807.

Janjua, S. & Hassan, I. 2020 Use of bankruptcy methods for resolving interprovincial water conflicts over transboundary river: case study of Indus River in Pakistan. *River Research and Applications* **36** (7), 1334–1344. https://doi.org/10.1002/rra.3621.

Jiang, G. Y. 2008 Discussion on maintenance and management of informationization equipment in long distance water supply project. *Water Resources and Power* **26** (03) 116–117.

Kedzior, S. B. 2017 "Preemptive participation' and environmental awareness across Indian water quality policy. *Journal of Environment and Development* **26** (3), 272–296. https://doi.org/10.1177/1070496517697768.

Kwon, K. K. & Han, S. H. 2006 River embankment stability against hydraulic piping failure in Korea. *Journal of the Korean Society of Civil Engineers C* **26** (1C), 33–42.

Lee, C. W., Maeng, Y. S. & Kim, Y. S. 2014 Behavior of Fill Dam subjected to continuous water level change and overflow. *Journal of The Korean Geoenvironmental Society* **15**, 41–48. https://doi.org/10.14481/jkges.2014.15.6.41.

Li, M. Y. & Cao, P. P. 2019 Extended TODIM method for multi-attribute risk decision making problems in emergency response. *Computers and Industrial Engineering* **135**, 1286–1293. https://doi.org/10.1016/j.cie.2018.06.027.

Li, H., Guo, Y., Li, F., Cao, Y., Wang, L. & Ma, Y. 2022 Assessment of operation safety risk for South-to-North water diversion project: a fuzzy VIKOR-FMEA approach. *Water Supply* **22**, 3685–3701. https://doi.org/10.2166/ws.2022.009.

Liu, H. C., You, J. X., You, X. Y. & Shan, M. M. 2015 A novel approach for failure mode and effects analysis using combination weighting and fuzzy VIKOR method. *Applied Soft Computing* **28**, 579–588. https://doi.org/10.1016/j.asoc.2014.11.036.

Liu, M., Cheng, Y. H. & Dong, J. 2016 Effectiveness of treatment measures for expansive soil slope in the middle route of the South-to-North water transfer project. *Journal of Yangtze River Scientific Research Institute* **33** (03), 104–110.

Liu, M. K., Yang, J. & Guan, G. H. 2020 Frazil jam risk assessment for water diversion projects. *Water Supply* **20**, 428–439. https://doi.org/10.2166/ws.2019.181.

Lu, X. Z., Cheng, Q. & Xiong, C. 2021 Regional seismic-damage prediction of buildings under mainshock–aftershock sequence. *Frontiers of Engineering Management* **8** (1), 122–134. https://doi.org/10.1007/s42524-019-0072-x.

Mamdani, E. H. 1974 Application of fuzzy algorithm for simple dynamic plant. *Proceedings of the Institution of Electrical Engineers* **121**, 1585–1580. https://doi.org/10.1049/piee.1974.0328.

Mamdani, E. H. 1976 Advances in the linguistic synthesis of fuzzy controllers. *International Journal of Man-Machine Studies* **8**, 669–678. https://doi.org/10.1016/S0020-7373(76)80028-4.

Nie, X. T., Fan, T. Y., Dong, H. & Wang, B. 2019 IOWA-Cloud model-based study on risk assessment of operation safety of long distance water transfer project. *Water Resources and Hydropower Engineering* **50**, 151–160. https://doi.org/10.13928/j.cnki.wrahe.2019.02.022.

Nie, X., Zhao, T., Zhang, P., Fan, T. & Wang, B. 2022 Study on risk correlation analysis and risk transmission of long-distance water diversion project. *Journal of North China University of Water Resources and Electric Power(Natural Science Edition)* **43**, 45–53. https://doi.org/10.19760/j.ncwu.zk.2022020.

Romero, E. & Jommi, C. 2008 An insight into the role of hydraulic history on the volume changes of anisotropic clayey soils. *Water Resources Research* **44** (5), 524–529. https://doi.org/10.1029/2007WR006558.

Song, W. Y., Ming, X. G., Wu, Z. Y. & Zhu, B. T. 2013 Failure modes and effects analysis using integrated weight-based fuzzy TOPSIS. *International Journal Computer Integrated Manufacturing* **26**, 1172–1186. https://doi.org/10.1080/0951192x.2013.785027.

Wang, Z. 2021 Current status and prospects of reliability systems engineering in China. *Frontiers of Engineering Management* **8** (4), 492–502. https://doi.org/10.1007/s42524-021-0172-2.

Wang, W., Cao, M. K., Shi, H. S., Zhang, Y. X. & Zhang, Y. 2016 Study on flood carrying and drainage capacity of a regional main tidal river. *Water Resources and Hydropower Engineering* **47** (5), 162–166.

Wang, L., Yuan, C., Li, H., Li, F. & Li, W. 2021 Risk evaluation of the middle route of South-to-North water diversion main channel project based on pythagorean fuzzy AHP. *China Rural Water and Hydropower* (01), 152–157 + 161.

Weaver, K. C., Cox, S. C., Townend, J., Rutter, H., Hamling, I. J. & Holden, C. 2019 Seismological and hydrogeological controls on New Zealand-wide groundwater level changes induced by the 2016 M-w 7.8 Kaikoura Earthquake. *Geofluids* **18**. https://doi.org/10.1155/2019/9809458.

Xi, W., Lu, W. G. & Xu, B. 2019 The inlet flow pattern of Tongcheng Gate and its improvement measure. *Journal of Yangzhou University(Natural Science Edition)* **22**, 74–78.

Xiong, Y. H., Qi, W. G. & Wang, Z. J. 2010 Operation risk study on the middle route of the South-to-North water diversion project (part I)–risk identification in the middle route of the South-to-North water diversion project. *South-to-North Water Transfers Water Science and Technology* **8** (03), 1–5.

Zhao, R. H., Qi, Z., Wang, X. J., Zhao, Y. & Zhang, L. Z. 2018 Risk identification and assessment of the accidents for distance water transfer project. In: *2018 4th International Conference on Green Materials and Environmental Engineering*, LancasterDestech Publications, Lancaster.

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