



Decision-Making Framework, Enhanced by Mutual Inspection for First-Stage Dam Construction Diversion Scheme Selection

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Abstract

Construction diversion is necessary for damming, and First-Stage Diversion Scheme Selection (FDSS) is of significance in damming process control. To effectively select the first-stage diversion scheme, a theoretical Decision-Making Framework (DMF) is presented and its decision-making basis includes diversion risk, costs, social attitudes and duration. With multiple aspects of concerns, the FDSS can be solved by Multi-Attribute Decision Making (MADM) methods and the complex diversion risk assessment can be achieved by the Monte Carlo Simulation (MCS). Mutual Inspection (MI) is based on a MADM feature of Partially Different Results (PDR), which should involve different MADM methods in solving the same problem and can reduce method difference-derived error within MADM results by mutually contrasting the PDR and refining ranking messages. Basing on these theoretical studies, the DMF for FDSS is developed, which contains two parts, the Risk Detector that assesses diversion risk of alternatives through MCS and the Decision Solver that undertakes decision-making preliminary and MADM enhanced by MI for solving FDSS. To demonstrate the DMF with MI, a case study that applies suitable MADM methods (viz. TOPSIS and ELECTRE I) for carrying out MI is conducted. Case results show that the DMF can solve the FDSS as it selects the optimal (S6) among six alternatives, the MI can enhance the DMF as it refines ranking messages about alternatives in the final MADM results. The DMF with MI can benefit the damming industry and contribute to the overall water resources management.

Keywords Water resources development · Damming · First-stage diversion · Scheme selection · Multi-attribute decision making enhancement

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1 Introduction

Dams are major tools for basin water resources management, and damming trend relates with world economy and population growth (Chen et al. 2016). Since demands increase rapidly in water supply, flood proofing, and hydroelectricity (Yazdi and Moridi 2018), world damming market in the near future will keep growing (Shi et al. 2019). Construction diversion is necessary for damming (Afshar et al. 1994), because dams are constructed in the river bed, where river-origin influence exists and should be avoided (Su and Tung 2012). Through diversion, river is diverted to bypass the worksite thus forming a dry and suitable bed for damming (Dai et al. 2006), and diversion is divided into stages along with the construction (Yuan and Hu 2009). The first-stage diversion that involves temporary structures like water-blocking cofferdams, diversion tunnels or channels should receive attention, as it is the diversion startup and leads the overall damming (Hu et al. 2006; Marengo et al. 2013). Figure 1 illustrates first-stage diversion scenario with a satellite photo (Google Maps 2019) of a typical project in China and a usual first-stage diversion layout sketch.

Intensive in labor and high in investment, damming process control attracts attention (Siciliano et al. 2015). As a key guidance in the initial damming, the First-Stage Diversion Scheme (FDS) needs carefully determination, because poor schemes can incur excessive costs, delay and even accidents (Hu et al. 2006; Marengo et al. 2013), and major damming accidents caused by diversion failure not merely bring huge loss but also impair public confidence in the government and hinder ongoing water resources development (Bozorg-Haddad et al. 2016; Su and Tung 2012). Currently, selection among diversion schemes relies heavily on expert's experience or stakeholders' will (Yuan and Hu 2009), and diversion failure happens (Marengo 2006). Hence, developing systematic and reliable decision-making tools for selecting FDSs is of significance.

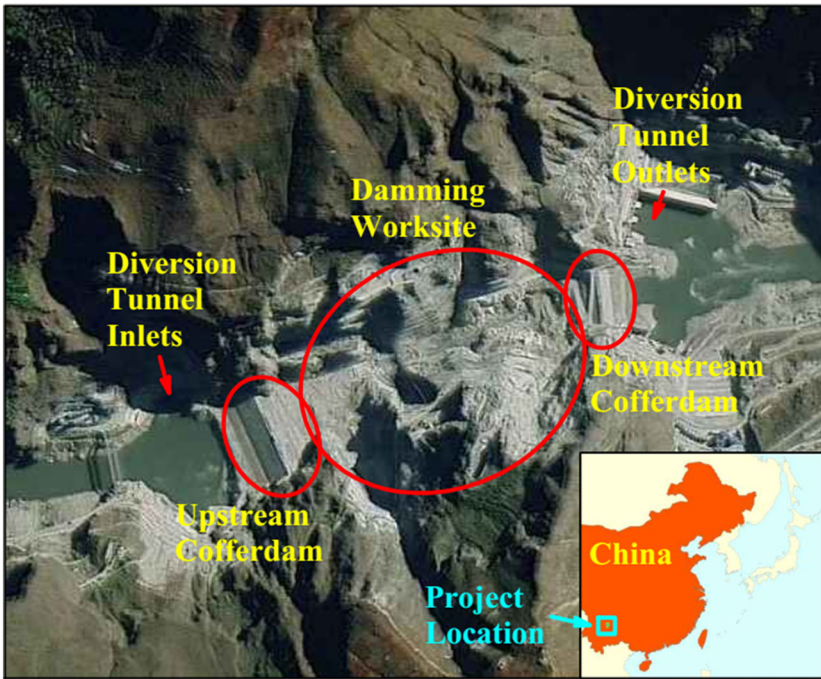
Among existing construction diversion literatures, focuses are placed on risk investigation or optimization. Studies showed, direct diversion risk source was the extreme flood (Marengo 2006); diversion risk rooted in uncertainties of diversion structures and the diversion environment (Afshar et al. 1994; Bozorg-Haddad et al. 2016); diversion risk could be assessed through simulation considering diversion uncertainties (Song et al. 2018), or hydrologic calculation with successive approximations (Marengo et al. 2013). With diversion risk assessed, further optimization could be reached by diversion standard design (Hu et al. 2006) and risk-cost tradeoff (Rasekh et al. 2010; Su and Tung 2012), as economic investment could elevate diversion standard and reduce risk.

From literature review, the current research gap is revealed, i.e. organized and practical researches specifically for diversion scheme selection are needed but lacked. Hence, this paper addresses the problem of First-Stage Diversion Scheme Selection (FDSS), and presents a feasible and effective theoretical framework for selecting FDS, namely the Decision-Making Framework (DMF). A novel approach named Mutual Inspection (MI) for decision enhancement is proposed as a part of the DMF.

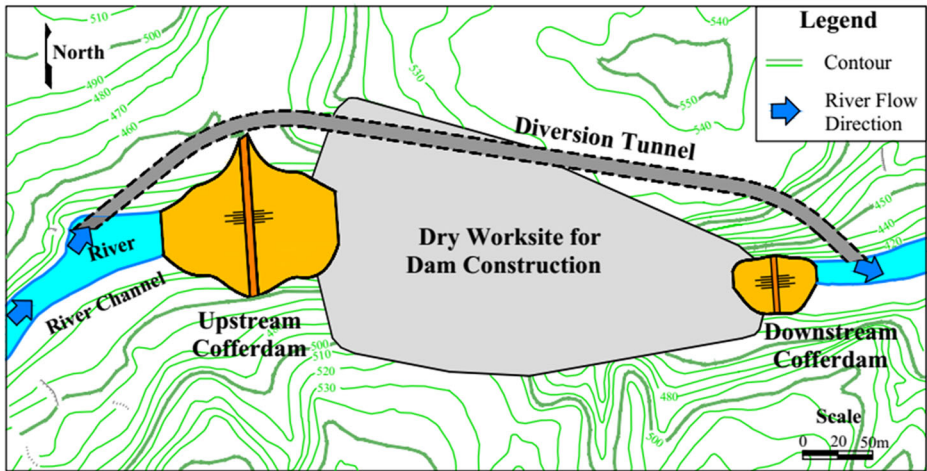
Rest of the paper includes: Theoretical Studies analyze decision-making basis, research methods, and detailed explains the MI, thus providing the theory of DMF; Methodology detailed explains the DMF; Case Study introduces a project case to demonstrate the DMF with MI. Discussion and Recommendations are drawn after the case study, and finally Conclusions are made.

2 Theoretical Studies

FDSS decision making clearly involves diversion risk and costs, whereas less-discussed factors like duration, attitudes toward FDSs should also be concerned. Because, timesaving is an advantage,



(a)



(b)

Fig. 1 First-stage Diversion Illustrations **a**: Typical Chinese Damming Project in Its First-Stage Diversion; **b** Usual Layout Sketch

attitudes reflect social aspects of consideration in water resources management and listening to attitudes from the public, the government, and engineers enhances the social acceptance. Hence, scheme’s diversion risk, costs, social attitudes and duration together form the decision-making basis for selection, and FDSS can be seen as the Multi-Attribute Decision Making (MADM).

In the aspect of research methods, MADM methods and diversion risk assessment methods should be highlighted, because MADM solves FDSS, within the decision-making basis, risk assessment is complex while costs can be calculated, information related to attitude and duration can be inquired. In water resources management studies that involve MADM, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Brankovic et al. 2018), the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (Haghshenas et al. 2016), the Multi-Attribute Utility Theory (MAUT) and Elimination et Choice Translating Reality (ELECTRE) (Ezbakhe and Perez-Foguet 2018) all showed good usability. Feasible methods in diversion risk assessment included the Monte Carlo Simulation (MCS) (Bozorg-Haddad et al. 2016; Song et al. 2018), the first-order reliability moment method (Marengo et al. 2013), the first-order second-moment analysis (Afshar et al. 1994), and MCS was more popular as it suited the scenario that involves multiple uncertainties.

Summing up, for the addressed problem of FDSS, its decision-making basis includes attributes of risk, costs, attitudes, and duration. Among them, diversion risk can be assessed by MCS, while others can be calculated or inquired. Then basing on MADM methods, alternatives i.e. FDSs, can be ranked and the optimal scheme is selected. Following this manner, the FDSS problem in general can be solved, which constitutes the solving part of DMF theory.

The presented DMF is expected to be practical and effective, as its attribute determination is settled, effort can be made on the decision making part to enhance the DMF. Studies have revealed that, for a given MADM problem, there are no best-suited methods (Hatamimarbini and Tavana 2011). Because, different applicable MADM methods yield similar but not identical ranking results for the same problem (Ozcan et al. 2011), and judging “result correctness” is hard. This phenomenon of Partially Different Results (PDR) is common in MADM, which carries useful information for decision making enhancement (Opricovic and Tzeng 2007). In authors’ opinion, PDR comes from differences among different MADM method, and inconsistent parts of PDR are the outcome of method differences influence, which can be seen as one decision-making error source. Basing on this opinion, an approach named Mutual Inspection (MI) is come up with. MI should involve more than one different MADM methods in solving the problem thus generating PDR, then mutually contrasting PDR so that consistency and inconsistency among results of different methods can be revealed. Ranking messages of alternatives within the consistent part of PDR are well-supported thus are credible, while ranking messages within the inconsistency part of PDR are weakly-supported thus are more likely to be influenced by method differences. Hence, filtering out weak ranking messages to refine the final results can reduce method difference-derived error and enhance the overall MADM. For MI, adding methods can make support/nonsupport among result messages evident and choosing methods with obvious differences can make decision inconsistency prominent. As method differences drives the MI to enhance decision making, choosing obvious different methods is more effective and method differences need analysis.

Differences among commonly-applied MADM methods include: (i) Differences in decision theories, like Analytic Hierarchy Process (AHP) and MAUT are utility function-based; PROMOTHEE and ELECTRE are outranking-based (Cinelli et al. 2014); TOPSIS and ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) are aggregating function-based (Opricovic and Tzeng 2004). (ii) Differences in result forms, like results of PROMETHEE GIGA bases on graphs, results of TOPSIS and VIKOR bases on “distance”, (Behzadian et al. 2010); AHP, MAUT, TOPSIS provide complete ranking, while ELECTRE I provides incomplete ranking, PROMETHEE I provides partial ranking (Caterino et al. 2009;

Lee and Chang 2018). (iii) Differences in information utilization, like ELECTRE, AHP better utilize attributes information than TOPSIS (Hatamimarbini and Tavana 2011). (iv) Differences in practice include, AHP, MAUT can better evaluate intangible attributes, but are cognitively demanding as utility function needs decision-maker judgment (Cinelli et al. 2014); TOPSIS, VIKOR suit decision scenario with mostly tangible attributes as more numerical calculation involved (Opricovic and Tzeng 2007); ELECTRE, PROMETHEE suit different decision scenario as they both have multiple versions. Thresholds values are noteworthy, as thresholds affect degree of compensation among different attributes. Indifference, preference, and veto thresholds help evaluating imperfect knowledge, and are used in PROMETHEE, ELECTRE Iv, III, IV, and TRI (Behzadian et al. 2010; Govindan and Jepsen 2016) etc., while the basis ELECTRE version of ELECTRE I just uses concordance and discordance indexes as thresholds values for Boolean Matrix formation (Anojkumar et al. 2014; Ozcan et al. 2011).

In this section, theoretical basis of the DMF are studied, include the FDSS solving manner and the MI for enhancement. Aiming at better demonstration, attributes of the FDSS decision-making basis shall be transformed into tangible values and reduce the imperfect knowledge to form a concise MADM scenario so that the paper can emphasize on presenting the performance of DMF with MI. For the followed case study, MADM methods of TOPSIS and ELECTRE I are suggested for carrying out MI, because these two basis methods are capable and easy to operate for the FDSS, suitable under tangible attributes, and evidently different in theories, result forms, and information utilization degree.

3 Methodology

3.1 Decision-Making Framework

Basing on the Theoretical Studies, the Decision-Making Framework for the addressed problem of First-Stage Diversion Scheme Selection is developed. The DMF contains two parts, a Risk Detector that assesses diversion risk of alternatives through MCS, and a Decision Solver that undertakes MADM and MI enhancement for solving FDSS. The structure and procedures of the DMF is shown in Fig. 2.

Known data can be obtained from local hydrology stations, provided or calculated according to FDS design. To further explain the DMF, working details of the Risk Detector and the Decision Solver are explained in below.

3.2 Risk Detector Adopts MCS

The Risk Detector adopts MCS for risk assessment, and in this section, diversion risk definition and the assessment formula are firstly described followed with working steps of the Risk Detector.

Diversion risk is defined as the uncertainty based impact posed on diversion objectives (ISO 2009), and diversion risk degree can be interpreted as the occurrence probability of major diversion accidents under diversion uncertainties. As explained in the Introduction, extreme flood is the main source of diversion risk and cofferdam overtopping by flood damages the damming condition i.e. diversion objectives, thus once cofferdam overtopping probability during a diversion is used in this paper to assess diversion risk, see Formula (1).

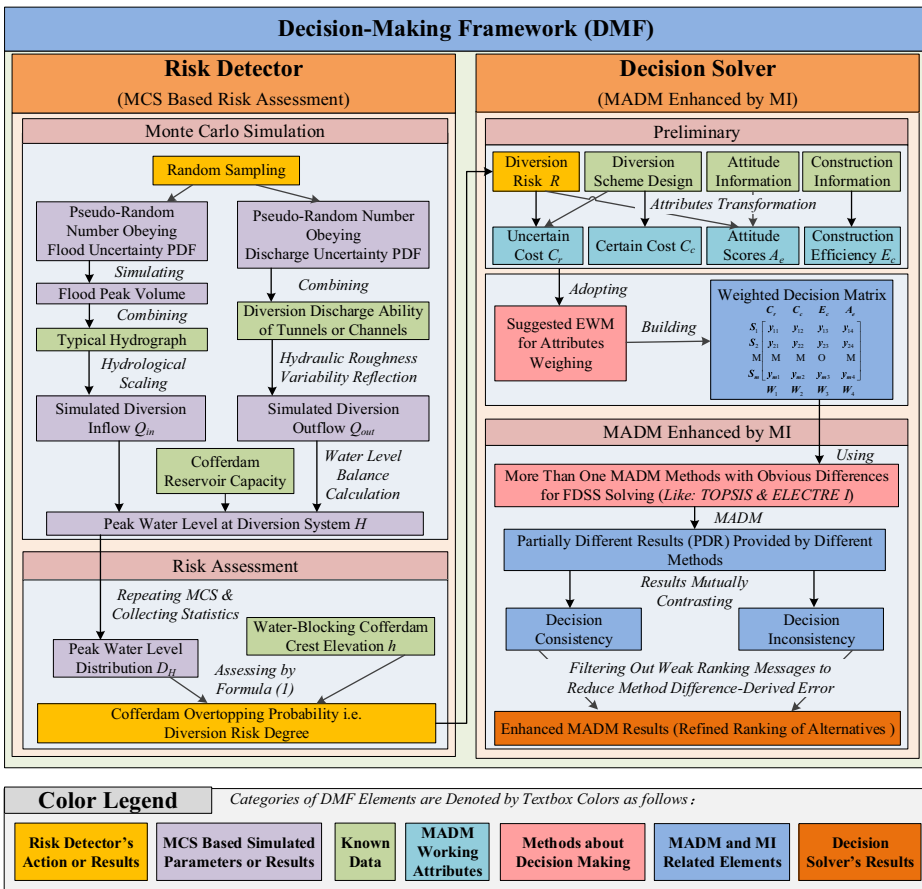


Fig. 2 Decision-Making Framework

$$R = P[H > h] \quad H \in D_H \tag{1}$$

Here, R is the diversion risk degree of an alternative (FDS), H is the possible peak water level at the diversion system (flood load for the cofferdam), h is the elevation of water-blocking cofferdam; $P[H > h]$ is the probability that H is higher than h ; D_H is the value distribution of H .

To obtain R , possible peak water level H and its distribution D_H are important, and through MCS, diversion uncertainties are reflected and a possible flood evolution during diversion is simulated, thus generating H . Main diversion uncertainties are flood uncertainty that influences flood courses during diversion i.e. diversion inflow Q_{in} and discharge uncertainty that influences discharge ability of diversion tunnels or channels i.e. diversion outflow Q_{out} . Hydrology data-based statistics helps determining the description of flood uncertainty and discharge uncertainty is related to roughness variability of the diversion tunnels or channels. Flood uncertainty description varies by regions and the Chinese code supports the Pearson III distribution, while discharge uncertainty description can adopt the Triangular distribution (Bureau of Reclamation 1987; Ministry of Water Resources 2017). Hence, in this paper, flood uncertainty uses the Pearson III distribution and discharge uncertainty uses the Triangular

distribution for description. Probability Density Functions (PDFs) of the two distribution are provided in the supplemental material, as Formula (S1) and Formula (S3).

According to Fig. 2, the Risk Detector carries out in steps:

- (1) **Expression of Diversion Uncertainties.** Through MCS random sampling, two sets of pseudo-random numbers belong to $[0,1]$ that respectively obeys PDFs of flood uncertainty and discharge uncertainty are generated. Pseudo-random numbers express diversion uncertainties, and are used to simulate diversion inflow and outflow;
- (2) **Simulation of Diversion Inflow and Outflow.** For diversion inflow Q_{in} , firstly, a flood peak volume is simulated basing on the pseudo-random number and watershed hydrology data. Then, this flood peak volume is combined with the local typical hydrograph through hydrological scaling to form a flood course as diversion inflow that possesses flood uncertainty and in accordance with local hydrological characteristics. For diversion outflow Q_{out} , the pseudo-random number is combined with the diversion discharge ability by reflecting hydraulic roughness variability during discharge volume calculation so that the diversion outflow that possesses discharge uncertainty and reflects FDS design is generated;
- (3) **Determination of the Peak Water Level and Its Value Distribution.** Using Q_{in} , Q_{out} , and collected data of cofferdam reservoir storage capacity, peak water level H at the diversion system is obtained through water balance calculation, and hereto once MCS completes. By repeating MCS in large times and collecting enough statistics on values of possible H , the peak water level value distribution D_H is obtained;
- (4) **Diversion Risk Assessment.** With D_H , and the water-blocking cofferdam crest elevation h , cofferdam overtopping probability is determined according to the Formula (1). Hence, the diversion risk degree R of a FDS is assessed.

3.3 Decision Solver Adopts MADM Enhanced by MI

The Decision Solver adopts MADM enhanced by MI to solve FDSS problem. As is decided in Theoretical Studies section, a concise MADM scenario is needed. Thus, among decision-making basis, intangible attributes of diversion risk and social attitudes need to be transformed into tangible attributes and duration needs transformation to reduce imperfect knowledge, then further MADM are proceeded.

According to Fig. 2, the Decision Solver carries out in steps:

- (1) **Preliminary.** Diversion risk relates closely to costs in terms of uncertainty and influences social attitudes as risk matters to the society. Thus, basing on R determined by the Risk Detector and FDS design, uncertainty cost C_r that reflects economic losses brought by diversion risk events is obtained, and certain cost, C_c is calculated according to the diversion design to reflect the diversion investment. R also provides reference for attitude evaluation along with environmental concerns and engineers' preference etc. Thus, basing on inquired information, social attitudes is evaluated by experts in the form of scores A_e . Duration is represented by construction efficiency of main diversion structures, E_c , to exclude factors unrelated to FDSs, like weather, holidays, labor disputes etc. As a result, decision-making basis attributes are transformed into four working attributes of C_r , C_c , E_c , A_e , and a concise MADM scenario is formed.

- (2) **Building the Weighted Decision Matrix.** To proceed MADM, a weighted decision matrix is needed. Entropy Weight Method (EWM) as one of the most commonly-used weighing methods with distinct principle (Feng et al. 2019; Hwang and Yoon 1981) is suggested and used for attributes weighing. Form of the weighted decision matrix is in Matrix (2).

$$\begin{matrix}
 & C_r & C_c & E_c & A_e \\
 S_1 & \left[\begin{array}{cccc}
 y_{11} & y_{12} & y_{13} & y_{14} \\
 y_{21} & y_{22} & y_{23} & y_{24} \\
 \vdots & \vdots & \ddots & \vdots \\
 y_{m1} & y_{m2} & y_{m3} & y_{m4}
 \end{array} \right. \\
 S_2 & & & & \\
 \vdots & & & & \\
 S_m & & & & \\
 & W_1 & W_2 & W_3 & W_4
 \end{matrix} \quad (2)$$

Here, S_m is the m th alternative, and y is the attribute element of one alternative; W_1 to W_4 are EWM weights for the four working attributes, and their sum is “1”.

- (3) **MADM.** To solve FDSS, MADM basing on the weighted decision matrix is conducted. For further Mutual Inspection (MI), more than one MADM methods with differences (TOPSIS and ELECTRE I in this study) are used. MADM results contain messages about alternatives ranking (FDSs ranking), and different methods’ results are expected to be partially different i.e. PDR.
- (4) **MI Enhancement.** By mutually contrasting PDR, decision consistency and inconsistency are revealed. Ranking messages within the inconsistent part of PDR are weakly-supported and considered as influenced by method differences, thus the Decision Solver filters out these weak ranking messages to reduce method difference-derived error. Hence, MADM enhanced by MI is achieved as the final alternatives ranking is refined. The optimal FDS is selected according to the enhanced results.

Details about determining working attributes and carrying out MADM methods are provided in the supplementary materials as text, Table S1, and Formula (S4)–(S25) according to literatures (Anojkumar et al. 2014; Hwang and Yoon 1981; Yuan and Hu 2009). When applying ELECTRE I, the thresholds values for Boolean matrixes determination adopt the concordance and discordance indexes respectively as Formula (S21), (S23) show.

4 Case Study

Leading by the theoretical framework and methodology, a case study is presented.

4.1 Case Profile

A large-scale hydropower dam project is set as the case background. The project’s diversion system adopts a ten-year return period flood-resisting standard, and should divert the corresponding maximum river runoff volume of 5330 m³/s. The first-stage diversion lasts for one and half years and spans two flood seasons. Six FDSs are designed as alternatives, and their main design parameters are in Table 1.

Table 1 Design of first-stage diversion schemes as alternatives

Alternatives (Schemes)	Cofferdam Type*	Number of Diversion Tunnels	Diversion tunnel size (m)	Upstream Cofferdam crest elevation (m)	Downstream Cofferdam crest elevation (m)
S1	Type 1	2	12 × 14	579.9	553.7
S2	Type 2	2	12 × 14	579.6	553.5
S3	Type 3	2	12 × 14	579.6	553.7
S4	Type 1	1	17 × 19	580.3	553.6
S5	Type 2	1	17 × 19	580.0	553.4
S6	Type 3	1	17 × 19	580.0	553.6

*Type 1: upstream and downstream earth-rock structure cofferdams. Type 2: upstream and downstream Roller Compacted Concrete (RCC) structure cofferdams. Type 3: hybrid design of upstream RCC and downstream earth-rock cofferdams

4.2 Results of Risk Assessment

According to Fig. 2, the Risk Detector assesses diversion risk of the six alternatives by MCS in terms of once cofferdam overtopping.

Needed data includes parameters for determining diversion uncertainties PDFs (Table S2), the local typical hydrograph (Table S3), the diversion cofferdam reservoir storage capacity (Table S4), and calculated discharge ability of diversion tunnels in different designs (Table S5 and S6). Details about these data are provided in the supplemental material. Statistically validation of data about diversion uncertainties, hydrograph, cofferdam reservoir, and diversion design is guaranteed as the case is adapted from a real damming project in China, and the authors just utilizes the project's data of hydrology, geological exploration and the project.

With data prepared, the Risk Detector conducts MCS and repeats it for 1,000,000 times so that the peak water level distribution D_H is generated, and values of h is shown in Table 1 as upstream cofferdam is the water-blocking cofferdam. Thus diversion risk results R of alternatives are obtained by Formula (1). Since the case first-stage diversion spans two flood seasons, the dynamic risk should be considered, i.e. probabilities of different risk event occurrence combinations in the two flood seasons. Dynamic risk degree are calculated with R by Formula (S4) in the supplemental material.

Results of R and dynamic risk of alternatives are shown in Table 2.

Table 2 Results of risk and dynamic risk of alternatives

Alternatives (Schemes)	Diversion risk degree R (%)	Condition I* Occurrence probability (%)	Condition II* Occurrence probability (%)	Condition III* Occurrence probability (%)
S1	10.19	9.15	1.04	80.66
S2	10.30	9.24	1.06	80.46
S3	10.30	9.24	1.06	80.46
S4	10.22	9.18	1.04	80.60
S5	10.31	9.25	1.06	80.44
S6	10.31	9.25	1.06	80.44

*Condition I denotes the occurrence of risk event in either the 1st or 2nd flood season; Condition II denotes the occurrence of risk event in all two flood seasons; Condition III denotes the safety diversion in all two flood seasons

4.3 Results of Decision-Making Preliminary

According to Fig. 2, the Decision Solver’s Preliminary first determines values of working attributes C_r , C_c , $E_c A_e$, then builds the weighted decision matrix for MADM.

Uncertain cost is calculated according to Formula (S5) basing on R -derived dynamic risk results in Table 2, and risk losses. According to FDS design, risk losses C_i are experientially estimated and provided in Table S7; Certain cost is calculated according to Formula (S6) just basing on diversion investments. According to FDS design, diversion investments C_i is experientially estimated and provided in Table S8. Details about these formulas and data are provided in the supplemental material. Case costs results of C_r , C_c are shown in Table 3. Construction efficiency as the construction information is provided by contractors, and case construction efficiencies of E_c are shown in Table 3.

Attitude information is inquired from the government, the public and engineers by any suitable means like consultation or investigation, and main concerns include risk, environmental issues and engineering difficulty. Addressing these concerns, several attitude evaluation criteria basing on social attitude are provides as the scoring references. Basing on the criteria, experts (virtual reference here, without strictly number requirement) can evaluate alternatives in terms of social attitude and score alternatives according to the “0 to 100” scoring system in Table S1. Case attitude scores of A_e as well as the attitude evaluation criteria are shown in Table 3.

With Table 3, adopting the EWM to weight each attribute, and the weighted decision matrix is built as Matrix (3).

Table 3 Case working attributes values and attitude scoring basis

Alternatives (Schemes)	Uncertain Cost C_r (million Yuan)	Certain Cost C_c (million Yuan)	Construction efficiency E_c ($\times 10^3$ m ³ /month)	Attitude Score A_e^* (Centesimal)
S1	28.82	412.03	13.50	59
S2	26.74	415.10	16.40	70
S3	24.66	414.50	15.80	68
S4	28.92	338.83	13.50	55
S5	26.75	342.03	16.40	66
S6	24.68	341.43	15.80	64
Attitude Evaluation Criteria (Risk)	Attitude Evaluation Criteria (Environmental)		Attitude Evaluation Criteria (Engineering)	
The society are risk averse, so low-risk schemes are more favored than high-risk schemes.	Single-tunnel schemes are better than double-tunnel schemes for less environmental impact as less site space occupation required; RCC cofferdams are better than earth-rock cofferdams as less excavated raw material required.		Double-tunnel schemes are easier to carry out than single-tunnel schemes for smaller size of tunnels; RCC cofferdam are easier to carry out than earth-rock cofferdam for smaller cofferdam body and higher degree of mechanization.	

*More detail about the attitude scoring can be found in in the supplemental material as the context in Results Supplementary

$$\begin{matrix}
 & C_r & C_c & E_c & A_e \\
 \begin{matrix} S1 \\ S2 \\ S3 \\ S4 \\ S5 \\ S6 \end{matrix} & \begin{bmatrix} 28.82 & 412.03 & 13.50 & 59 \\ 26.74 & 415.10 & 16.40 & 70 \\ 24.66 & 414.50 & 15.80 & 68 \\ 28.92 & 338.83 & 13.50 & 55 \\ 26.75 & 342.03 & 16.40 & 66 \\ 24.68 & 341.43 & 15.80 & 64 \end{bmatrix} \\
 & & & & \\
 W_j & C_r & C_c & E_c & A_e \\
 & 0.217 & 0.425 & 0.206 & 0.152
 \end{matrix} \tag{3}$$

Weighing process includes the objective weight calculation and subjective weight assign follows the working principle of the EWM in Formula (S7)–(S11), which is described in in the supplemental material as the context in Results Supplementary and Table (S9).

4.4 Results of MADM and MI Enhancement

According to Fig. 2, with the weighted decision matrix, the Decision Solver conducts MADM enhanced by MI to solve the FDSS.

The case adopts TOPSIS and ELECTRE I follows Formula (S12)–(S25) in the supplemental material. MADM Results of TOPSIS and ELECTRE I are presented in Table 4.

As Table 4 shows, basing on the closeness of TOPSIS *RD* to “1”, the alternatives ranking results of TOPSIS is obtained, and main ranking messages are: (i) S6 is the optimal one among the six alternatives as its *RD* is the closest to “1”; (ii) S6 precedes S5 precedes S4 precedes S3 precedes S2 precedes S1;(iii) All single-tunnel schemes (S4, S5, S6) precede double-tunnel schemes (S1, S2, S3).

Meanwhile, basing on the ELECTRE I’s Dominance Matrix, the alternatives ranking results of ELECTRE I is obtained, and main ranking messages are: (i) S6 is the optimal one among the six alternatives as it is not dominated by any other scheme; (ii) S6 dominates S5–1, S5 dominates S4–1, S3 dominates S2–1, and S2 dominates S1; (iii) S4 only dominates S1;(iv) Relations between “S4 to S2” and “S4 to S3” are neither dominating or being dominated.

Evidently, results of the two methods of TOPSIS and ELECTRE I are partially different, thus forming the PDR, and MI can be proceeded. In MI, two method results are mutually contrasted to reveal the decision consistency and inconsistency:

Table 4 MADM Results of TOPSIS & ELECTRE I

Alternatives (Schemes)	TOPSIS <i>RDs</i>	TOPSIS alternatives ranking	ELECTRE I Dominance matrix*	ELECTRE I alternatives ranking	
S1	0.092	S6→S5	$ \begin{matrix} S1 & S2 & S3 & S4 & S5 & S6 \\ \begin{bmatrix} - & 0 & 0 & 0 & 0 & 0 \\ 1 & - & 0 & 0 & 0 & 0 \\ 1 & 1 & - & 0 & 0 & 0 \\ 1 & 0 & 0 & - & 0 & 0 \\ 1 & 1 & 1 & 1 & - & 0 \\ 1 & 1 & 1 & 1 & 1 & - \end{bmatrix} \end{matrix} $	S6→S5→S4	
S2	0.390	✓		✓	↓
S3	0.395	S4→S3			S3→S2→S1
S4	0.575	✓			
S5	0.830	S2→S1			
S6	0.853				

*In the ELECTRE I’s Dominance Matrix, “1”denotes that the row scheme dominates the column scheme, and “0” denotes the contrary message. When situations like S2 and S4 occur (both got 0 toward the other), we consider that the method cannot give the dominance relation between them i.e. neither dominating or being dominated

- (1) **Decision consistency.** Main consistent ranking messages are: (i) S6 is the optimal one among the six alternatives; (ii) S6 precedes S5 precedes S4; (iii) S3 precedes S2 precedes S1.
- (2) **Decision inconsistency.** Main inconsistent ranking messages are: (i) S4 precedes S3 precedes S2, by TOPSIS; (ii) All single-tunnel schemes precede double-tunnel schemes, by TOPSIS; (iii) Single-tunnel scheme S4 does not dominate Double-tunnel scheme S2 or S3, by ELECTRE I.

As inconsistent results messages are weakly-supported and considered as influenced by method differences of TOPSIS and ELECTRE I, they are filtered out from the final results.

Finally, MADM enhanced by MI are completed, and for this case, the refined results are: (i) S6 is the optimal one among the six alternatives; (ii) S6 precedes S5 precedes S4; (iii) S3 precedes S2 precedes S1. Hereinto, the DMF solves the FDSS problem, as it selects the optimal FDS among six alternatives (S6, the design with hybrid cofferdams and single 17×19 diversion tunnel), along with other useful FDSs ranking information.

5 Discussion and Recommendations

In the case study, the presented DMF solves the FDSS problem that has six alternatives, and the MI helps filtering out weak ranking messages thus refining the final results. By analyzing the case solving process and results, constructive information is discussed to support the findings of the study, and recommendations for better DMF performance and future works are drawn:

- (1) **Involvement of Social Attitude.** Involving in social aspect of considerations in this study is contributive as social acceptance is less discussed in existing diversion literatures. For FDSS, considering the social attitude as one part of the decision-making basis is necessary, because, attitudes about risk, environmental, engineering all have potential to incur significant and far-reaching impacts not only on the project itself but also on the overall water resources development. Nowadays, concepts of construction industry are shifting from the traditional engineering feasibility primary to more comprehensive forms, and the humanized and environmental-friendly engineering is called for worldwide, and this study just responds to this modern need. In implementation, the DMF does reflect the social attitudes in its results, for example, case results (Table 3) show that: RCC cofferdam design is environmental-friendly and easier to carry out, thus RCC related alternatives of S6, S5, S4, S3 all gain advantages to earth-rock cofferdam schemes and the optimal alternative S6 has the RCC cofferdam as the main cofferdam. Summing up, involvement of social attitude in FDSS is contributive and necessary and the presented DMF can actually reflect this involvement.
- (2) **Necessity of Attributes Transformation.** FDSS decision-making basis includes attributes of diversion risk, costs, social attitudes and duration, while in this paper, they are transformed into working attributes of C_r, C_c, E_c, A_e to form the concise MADM scenario. Frankly, without this attributes transformation, the MADM can still give results to the FDSS, however the case study shows that with attributes transformation the decision-making basis is better expressed. Shown by Table 2, Table 3, among R of six alternatives, risk degree gaps are within 0.12%, while among R -related working attributes of C_r and A_e , the largest gaps among uncertain

costs is 4.26 million Yuan (about 14.7% of the highest cost, and 17.3% of the lowest cost) and among attitude scores is 15 (about 21.4% of the highest score, and 27.3% of the lowest scores). From this dramatic gaps contrast, it can be seen that sheer diversion risk degrees cannot fully express possible economical loss or social attitude influences, because more considerations like different scheme design and expert-based attitude evaluation involved. Transforming duration into E_c also contributes to the FDSS as irrelevant information is excluded. Since tangible C_r and A_e better express the intangible diversion risk losses and impact, social attitudes, and E_c helps reducing imperfect knowledge, attributes transformation is necessary for better DMF implementation.

- (3) **Performance of MI.** In the case study, MI does refine the final results. Table 4 shows that: TOPSIS and ELECTRE I yield similar but not identical results for the case problem, and their ranking messages in results have the similar trend, i.e. from S6 to S1 precedence in sequence. Only ranking messages about S4 are inconsistent between the two methods results. This situation accords with the MI theory description in the Theoretical Studies. Also, the case reveals that most ranking messages within the results are strong enough to be free from method difference influence so that MI may not filter out too many messages to cause distress. Hence, the case proves that MI enhancement is theoretically sound and practically effective.
- (4) **Recommendations.** On the basis of MI's theory, adding or changing applied MADM methods can improve its adaptation and performance so that study limitations like "optimal schemes given by different methods are different" or "no evident enhancement" can be dealt with.

The DMF is expandable to suit more diversion environment or involve more decision attributes. For example, diversion uncertainties like sediment uncertainty of sandy rivers may be involved in the risk assessment part; new attributes like sustainability or policy can be involved in the MADM as the decision-making basis, which are recommended for future works.

6 Conclusions

This paper develops a theoretical framework for the addressed problem of selecting first-stage diversion scheme, which aims at better damming process control. The presented DMF contains a Risk Detector that adopts MCS for alternatives' diversion risk assessment, and a Decision Solver that implements MADM enhanced by MI to provide refined scheme ranking results for solving FDSS. Case study results show that the DMF can select the optimal scheme among six alternatives, and the MI enhancement is effective as it filters out weak ranking messages influenced by methods differences and refines the final MADM results. Contributions of the study includes:

- (1) The DMF, enhanced by MI, is feasible and effective in selecting FDSs, which helps narrow the current research gap of lacking organized and practical researches specifically for diversion scheme selection. DMF and MI have industrial potential.
- (2) Within the DMF, involvement of social attitude in FDSS solving responds to the modern call of humanized and environmental-friendly engineering, and the DMF can reflect these social aspect of considerations in MADM and results. Attributes transformation is necessary for better implementing DMF as tangible working attributes can better express intangible decision-making basis of diversion risk and social attitude, and reduce imperfect knowledge.

- (3) MI as an innovative tool built on the MADM feature of PDR, can enhance the DMF by reducing method difference-derived error in MADM results. MI has distinct theory and can adapt to different decision situations by adding or changing applied methods.

The DMF and MI can play a positive role in the damming industry and contributes to the overall water resources management.

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Data Availability Data involved in this study is shown in the supplemental material and is available from the corresponding author by request.

Compliance with Ethical Standards

Conflict of Interest none.

References

- Afshar A, Barkhordary A, Marino MA (1994) Optimizing river diversion under hydraulic and hydrologic uncertainties. *J Water Resour Plan Manag* 120:36–47. [https://doi.org/10.1061/\(ASCE\)0733-9496\(1994\)120:1\(36\)](https://doi.org/10.1061/(ASCE)0733-9496(1994)120:1(36))
- Anojkumar L, Ilangkumaran M, Sasirekha V (2014) Comparative analysis of MCDM methods for pipe material selection in sugar industry. *Expert Syst Appl* 41:2964–2980. <https://doi.org/10.1016/j.eswa.2013.10.028>
- Behzadian M, Kazemzadeh RB, Albadvi A, Aghdasi M (2010) PROMETHEE: a comprehensive literature review on methodologies and applications. *Eur J Oper Res* 200:198–215. <https://doi.org/10.1016/j.ejor.2009.01.021>
- Bozorg-Haddad O, Orouji H, Mohammad-Azari S, Loáiciga HA, Marino MA (2016) Construction risk management of irrigation dams. *J Irrig Drain Eng* 142:04016009. [https://doi.org/10.1061/\(ASCE\)Ir.1943-4774.0001001](https://doi.org/10.1061/(ASCE)Ir.1943-4774.0001001)
- Brankovic JM, Markovic M, Nikolic D (2018) Comparative study of hydraulic structures alternatives using promethee II complete ranking method. *Water Resour Manag* 32:1–15. <https://doi.org/10.1007/s11269-018-2001-x>
- Bureau of Reclamation US (1987) Design of small dams. U.S. Department of the Interior, Bureau of Reclamation, Washington, DC
- Caterino N, Iervolino I, Manfredi G, Cosenza E (2009) Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. *Comput Civ Infrastruct Eng* 24:432–445. <https://doi.org/10.1111/j.1467-8667.2009.00599.x>
- Chen J, Shi H, Sivakumar B, Peart MR (2016) Population, water, food, energy and dams. *Renew Sustain Energy Rev* 56:18–28. <https://doi.org/10.1016/j.rser.2015.11.043>
- Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecol Indic* 46:138–148. <https://doi.org/10.1016/j.ecolind.2014.06.011>
- Dai HC, Cao GJ, Su HZ (2006) Management and construction of the Three Gorges Project. *J Constr Eng Manag* 132:615–619. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2006\)132:6\(615\)](https://doi.org/10.1061/(ASCE)0733-9364(2006)132:6(615))
- Ezbakhe F, Perez-Foguet A (2018) Multi-criteria decision analysis under uncertainty: two approaches to incorporating data uncertainty into water. *Sanit Hyg Plan Water Resour Manag* 32:5169–5182. <https://doi.org/10.1007/s11269-018-2152-9>
- Feng Y, Fanghui Y, Li C (2019) Improved entropy weighting model in water quality evaluation. *Water Resour Manag* 33:2049–2056. <https://doi.org/10.1007/s11269-019-02227-6>
- Google Maps (2019) Satellite Photo of a first-stage diversion project. [http://www.google.cn/maps/place/26°19'10.6"N+102°38'10.8"E](http://www.google.cn/maps/place/26°19'10.6)
- Govindan K, Jepsen MB (2016) ELECTRE: a comprehensive literature review on methodologies and applications. *Eur J Oper Res* 250:1–29. <https://doi.org/10.1016/j.ejor.2015.07.019>

- Haghshenas SS, Neshaei MAL, Pourkazem P, Haghshenas SS (2016) The risk assessment of dam construction projects using fuzzy TOPSIS (Case Study: Alavian Earth Dam). *Civ Eng J* 2:158–167
- Hatamimarbini A, Tavana M (2011) An extension of the Electre I method for group decision-making under a fuzzy environment. *Omega* 39:373–386. <https://doi.org/10.1016/j.omega.2010.09.001>
- Hu Z, Fan X-E, Liu Q, Huang H (2006) Design of integrated risk distribution mechanism of construction diversion system. *J Hydraul Eng* 37:1270–1277. <https://doi.org/10.3321/j.issn:0559-9350.2006.10.020> (in Chinese)
- Hwang C-L, Yoon K (1981) Multiple attributes decision making methods and applications; A State-of-the-Art Survey. Springer, Berlin
- ISO IOFS (2009) ISO 31000:2009 risk management – principles and guidelines. International Organization for Standardization, Geneva
- Lee H-C, Chang C-T (2018) Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. *Renew Sustain Energy Rev* 92:883–896. <https://doi.org/10.1016/j.rser.2018.05.007>
- Marengo H (2006) Case study: dam safety during construction, lessons of the overtopping diversion works at Aguamilpa Dam. *J Hydraul Eng* 132:1121–1127. [https://doi.org/10.1061/\(Asce\)0733-9429\(2006\)132:11\(1121\)](https://doi.org/10.1061/(Asce)0733-9429(2006)132:11(1121))
- Marengo HH, Arreguin FI, Aldama AA, Morales V (2013) Case study: risk analysis by overtopping of diversion works during dam construction: the La Yesca hydroelectric project. *Mexico Struct Saf* 42:26–34. <https://doi.org/10.1016/j.strusafe.2013.01.005>
- Ministry of Water Resources PRC (2017) SL 303–2017 specifications for construction planning of water resources and hydropower projects. Water&Power Press, Beijing
- Opricovic S, Tzeng G-H (2004) Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *Eur J Oper Res* 156:445–455. [https://doi.org/10.1016/s0377-2217\(03\)00020-1](https://doi.org/10.1016/s0377-2217(03)00020-1)
- Opricovic S, Tzeng G-H (2007) Extended VIKOR method in comparison with outranking methods. *Eur J Oper Res* 178:514–529. <https://doi.org/10.1016/j.ejor.2006.01.020>
- Ozcan T, Celebi N, Esnaf Ş (2011) Comparative analysis of multi-criteria decision making methodologies and implementation of a warehouse location selection problem. *Expert Syst Appl* 38:9773–9779. <https://doi.org/10.1016/j.eswa.2011.02.022>
- Rasekh A, Afshar A, Afshar MH (2010) Risk-cost optimization of hydraulic structures: methodology and case study. *Water Resour Manag* 24:2833–2851. <https://doi.org/10.1007/s11269-010-9582-3>
- Shi H, Chen J, Liu S, Sivakumar B (2019) The role of large dams in promoting economic development under the pressure of population growth. *Sustainability* 11:2965
- Siciliano G, Urban F, Kim S, Lonn PD (2015) Hydropower, social priorities and the rural–urban development divide: the case of large dams in Cambodia. *Energy Policy* 86:273–285. <https://doi.org/10.1016/j.enpol.2015.07.009>
- Song Z, Liu Q, Hu Z, Li H, Xiong J (2018) Assessment of sediment impact on the risk of river diversion during dam construction: a simulation-based project study on the Jing River, China. *Water* 10:217. <https://doi.org/10.3390/w10020217>
- Su H-T, Tung Y-K (2012) Flood-damage-reduction project evaluation with explicit consideration of damage cost uncertainty. *J Water Resour Plan Manag* 139:704–711. [https://doi.org/10.1061/\(asce\)wr.1943-5452.0000291](https://doi.org/10.1061/(asce)wr.1943-5452.0000291)
- Yazdi J, Moridi A (2018) Multi-objective differential evolution for design of cascade hydropower reservoir systems. *Water Resour Manag* 32:4779–4791. <https://doi.org/10.1007/s11269-018-2083-5>
- Yuan G, Hu Z (2009) Water conservancy construction. 5th edn. Water & Power Press, Beijing

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