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Identification and Ranking of Human Resource-Related Risks Considering Secondary and Residual Risks in Water Transfer Projects Using the DEMATEL–MARCOS Method

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Abstract: In competitive organizations and projects, assessing risks related to human capital is essential for improving workplace conditions and ensuring project success. This study evaluates primary, secondary, and residual human capital risks in urban water transfer projects using an innovative hybrid DEMATEL–MARCOS approach. The DEMATEL method was employed to analyze causal relationships and interdependencies among risks, while the MARCOS method ranked their significance. The key findings reveal that "accidents during material transportation" (primary risk), "corrosion" (secondary risk), and "pipeline pressure" (residual risk) are the most critical factors influencing human capital in such projects. The study provides a structured framework for prioritizing risk mitigation strategies, offering actionable insights for policymakers and project managers to enhance safety, efficiency, and workforce well-being. By integrating multi-criteria decision-making techniques, this research bridges a gap in the water industry's risk management practices and contributes to safer, more sustainable infrastructure development.

Keywords: water supply project; human capital risk; secondary risk; residual risk; multi-criteria decision making; DEMATEL; MARCOS

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1. Introduction

With increasing population growth, cities are expanding rapidly, leading to higher water consumption for various purposes [1–4]. Water supply and transfer projects play a crucial role in addressing water scarcity, ensuring sustainable resource management, and improving access to clean water in both urban and rural areas. Several studies have examined the sustainability and impact of water supply projects. For instance, the sustainability of community-based water supply initiatives has been extensively analyzed to determine the factors influencing their long-term success [5]. Similarly, the need for robust assessment tools in water supply and sanitation projects has been highlighted to ensure the effectiveness of technical and socioeconomic factors [6].

In the context of large-scale water transfer projects, numerous studies have investigated their implications on regional development and water security. For example, China's

South–North Water Transfer Project (SNWTP) serves as a major case study in understanding how large-scale water infrastructure influences resource availability and distribution [7]. Other research has explored global water transfer megaprojects as a potential solution for managing the water–food–energy nexus, analyzing their viability and long-term consequences [8]. A systematic review of the sustainability of inter-basin water transfer projects further outlined their environmental, social, and economic dimensions, emphasizing the need for a balanced approach to water management [9].

The socioeconomic and environmental impacts of these projects have also been widely debated. Several studies have highlighted the challenges faced by communities affected by large-scale water transfer projects, particularly in terms of displacement, changes in water availability, and economic consequences [10]. Moreover, the environmental changes induced by inter-basin water transfer projects in the United States underscore the significance of planning and ecological considerations in project execution [11]. The impact of large-scale water diversion projects on water supply networks, as observed in Southwest China, further provides empirical data on the consequences of such infrastructure developments [12]. Finally, innovative approaches to water management have been proposed to address the evolving challenges of water supply and transfer. A new conceptual model for inter-basin water transfer has been introduced to account for the changing dynamics of global water resources [13]. These studies collectively underscore the importance of sustainable water management practices, environmental conservation, and socioeconomic considerations in water supply and transfer projects.

Risk management is considered an essential and critical practice that enables precise decision-making based on the level of risk involved [14,15]. The PMBOK (Project Management Body of Knowledge) Guide defines risk as an uncertain event or condition that, if it occurs, may have a positive or negative impact on a project's objectives. A key aspect of this definition is that the effect of uncertainty, when realized, can either be beneficial or detrimental to the planned endeavor [16].

In today's complex and dynamic project environments, risk is one of the most critical factors that must be considered and managed to ensure the successful completion of projects [17]. Identifying, assessing, and responding to risks that water transfer projects may encounter is essential. Ignoring these risks can lead to additional costs and delays, ultimately resulting in project failure [18]. The risk management skills of executives reflect their ability to ensure project success [19]. Risk management involves multiple dimensions and stages that require thorough analysis [20]. According to PMBOK, seven key steps are proposed for risk management; however, in summary, the fundamental requirements are the identification, assessment, and response to risks [21].

Project risk management has been identified as a crucial factor requiring precise assessment to guarantee error minimization [22]. To enhance project performance, companies have increasingly adopted effective risk management strategies [23]. These strategies assist companies in improving the value generated across deliverables while maintaining competitiveness. Integrating these studies into the risk assessment framework of water supply and transfer projects allows for a more comprehensive understanding of potential hazards and the development of proactive management strategies. Although numerous studies on project risk management have been conducted in industries such as information technology and construction, a significant gap remains in the development of appropriate project risk management methods in the water industry [1–4].

Risk identification and management is an innovative approach used to enhance and improve organizational effectiveness. In general, risk is defined as the probability of loss or uncertainty and encompasses various types and classifications [24]. One classification differentiates between speculative risk and pure risk. All forms of risk share common

elements, including context, activities, conditions, and consequences. Another classification distinguishes between strategic risk and operational risk. Risk management involves assessing risks and then implementing strategies to manage them. Risks can be categorized based on their likelihood of occurrence and impact, leading to the creation of a risk portfolio and the application of appropriate strategies such as risk transfer, avoidance, reduction, and acceptance [25].

Effective risk management is a crucial aspect of water supply and transfer projects, ensuring their sustainability, safety, and efficiency. Several studies have emphasized the importance of risk assessment methodologies and mitigation strategies in these projects. For instance, Nguyen et al. [1] identified 26 primary risks leading to schedule delays in water supply construction projects in Hanoi, ranking them through survey analysis and providing targeted risk mitigation recommendations. Their findings serve as a valuable reference for investors and contractors aiming for timely project completion. Similarly, Chen et al. [4] conducted a systemic risk analysis for large-scale water transfer projects, employing Bayesian networks to assess risks related to safety, progress, and investment.

Furthermore, Su et al. [2] reviewed various risk analysis methods in water supply systems, emphasizing the necessity of preventive measures to ensure safe and continuous drinking water distribution. Additionally, a real-time risk monitoring model for water transfer projects was proposed by Zhao et al. [3], utilizing System Dynamics Models (SDMs) to quantify risk transmission between project components. Their approach provides a proactive strategy for risk management in large-scale infrastructure projects.

Flood control risks also pose significant challenges in water transfer projects. Chen et al. [26] systematically identified and classified such risks, advocating for hierarchical management approaches to enhance operational safety. Meanwhile, water pollution risks, particularly in large-scale transfer projects, were analyzed by Zhang et al. [27], who provided insights into pollution sources and their potential impacts, suggesting effective mitigation measures.

Ernst and Young [28], in a report titled “Global Human Resource Risks”, defined human capital risk as the risk associated with employee-related programs and processes, which, if managed effectively, can position an organization among market leaders. In another definition, human capital risk refers to the uncertainty arising from changes across a broad range of human resource management issues that impact an organization’s ability to achieve its strategic and operational objectives [29]. Bombiak [30] described human capital risk as encompassing both anticipated and unforeseen employee-related events that determine the extent to which organizational goals are achieved. Also, Bombiak [31] examined human resources risk as a critical aspect of HR management in turbulent environments, emphasizing both anticipated and unforeseen employee-related risks that impact organizational goal achievement. The study highlighted the importance of proactive HR risk management strategies to enhance organizational resilience and performance in dynamic business conditions.

One of the most valuable assets of any organization is its knowledgeable, experienced, and skilled workforce [32]. Human capital is the most critical resource for maintaining efficiency within any organization. However, various risks constantly threaten human capital [33]. Organizations facing human capital risks may lose their competitive advantages if they lose key personnel. The consequences of increasing these risks can be detrimental to both human capital and the organization as a whole. Therefore, mitigating the effects of such risks is essential for organizations to reduce risk-related costs, alleviate risk-induced stress, implement precise human capital planning, empower employees, and develop individuals’ real capabilities and competencies [34]. In addition, recognizing and prioritizing human capital as an organization’s greatest asset has gained significant attention over

the past two decades. Possessing experienced, competent, and knowledgeable personnel provides a substantial competitive advantage for any organization operating in a dynamic environment. Addressing both the material and psychological aspects of human capital, such as job satisfaction and motivation, enhances efficiency, quality, productivity, and overall organizational effectiveness. In the context of risk management, human resource challenges are examined from the perspective of future risks, potential vulnerabilities, and their impact on the quantity and quality of organizational outputs.

Recent studies on water transfer projects have predominantly focused on technical, environmental, and economic risks [1,4], while human capital-related risks, particularly secondary and residual risks, remain underexplored. For instance, Su et al. [2] identified 26 primary risks in water supply systems but omitted cascading effects (e.g., corrosion from material transportation accidents). Similarly, while DEMATEL (Decision-Making Trial and Evaluation Laboratory) has been applied to leakage risks in energy projects, its integration with MARCOS (Measurement of Alternatives and Ranking according to Compromise Solution) for hierarchical human capital risk assessment is novel. This gap is critical, as human factors account for 42% of delays in infrastructure projects. This study addresses the following question: "How can primary, secondary, and residual human capital risks in water transfer projects be systematically identified, analyzed, and prioritized to improve risk mitigation strategies?".

The present study aims to identify and rank human resource-related risks in water supply projects. This is achieved by identifying relevant risks based on previous research. Additionally, secondary risks, which arise from responses to primary risks, are examined, as well as residual risks—those expected to persist after implementing planned risk responses and those deliberately accepted.

This study employs the DEMATEL method, leveraging expert judgment to identify factors within a system and applying graph theory principles to extract causal and mutual relationships among elements [35,36]. This method provides a hierarchical and systematic structure by quantifying the intensity of these relationships numerically [37]. Finally, the MARCOS method is used to rank human resource-related risks.

Existing frameworks lack granularity in assessing interdependencies between risk layers (e.g., how welding errors (primary) accelerate corrosion (secondary)). By combining DEMATEL's causal mapping with MARCOS's ranking robustness, this study offers a replicable model for quantifying human-centric risks, a necessity underscored by Ernst and Young's findings [28] that 68% of project failures stem from unmanaged HR risks. The proposed hybrid approach advances the risk management guidelines of PMBOK (Project Management Body of Knowledge) by adding empirical specificity to water infrastructure contexts. In other words, the primary innovation of this research lies in proposing a hybrid DEMATEL–MARCOS model for analyzing human capital risk in water supply projects, integrating primary, secondary, and residual risks. The developed framework simultaneously accounts for the interrelationships among criteria and decision-making behavior, identifying risk factors and evaluation criteria through literature review and expert experience.

Table 1 summarizes previous studies on risk. A review of the empirical literature suggests that human capital risk varies across different industries. Additionally, the literature indicates that human capital-related risks represent a significant category of risk for organizations worldwide [38]. In practice, many organizations have a limited definition of human capital risk, which may result in leaders failing not only to identify fundamental risks but also to recognize improvement opportunities that could enhance organizational performance relative to competitors. Thus, research on this topic can assist water indus-

try managers in identifying and ranking human capital risks, enabling them to plan and implement measures for risk control and improvement.

Table 1. Summary of the literature review (the asterisk shows the study has considered or conducted that matter).

Author	Year	Case Study			Research Model		Risk Scope
		Energy	Production	Service	Quantitative	Qualitative	
Hsu [39]	2025		*		Network DEA		Sustainability-related supply chain risk management
Sunaryo et al. [40]	2025			*		Literature Review	Risk Management on Corporate Performance
Scott et al. [41]	2024			*		Literature Review	Risk in financial operations
Nnaji et al. [42]	2024			*		Literature Review	Risk management for supply chain finance
Okoye et al. [43]	2024			*		Literature Review	Risk Management in International Supply Chain
Ristanović and Knežević [44]	2023			*	MCDM		Banking operational risks
Badida et al. [45]	2023			*	MCDM		Health and safety risks in hospitals
Bussier and Chong [46]	2022		*		Statistical		Safety measures and human errors in the construction industry
Haghighi and Ashrafi [21]	2022	*			Mathematical Programming	*	Time–cost trade-off in projects from a risk management perspective
Balali et al. [47]	2021			*	MCDM		Human resource threats in supply projects
La Fata et al. [48]	2021			*	MCDM and Deep Learning		Flood risk assessment
Yazdani et al. [49]	2021			*	MCDM		Agricultural supply chain risk management
Khalilzadeh et al. [50]	2021	*			MCDM		Leakage-related accidents on offshore platforms
Karunathilake et al. [51]	2020			*	MCDM		A review of studies on risk management
Yan et al. [52]	2020		*		Neural network		Human resource management risk
Bid and Siddique [53]	2019		*		MCDM		Human resource risks at an Indian dam
Pham et al. [54]	2019			*	MCDM and Deep Learning		Flood risk assessment
Srinivasan et al. [55]	2018			*	Genetic Algorithm		Banks' financial risk management
Wang et al. [56]	2018	*			MCDM		Risk ranking in contracting projects
This study	2025	*			MCDM (DEMATEL–MARCOS)		Assessing risks related to human capital at three levels: primary, secondary, and residual risks

A review of the literature indicates that previous studies on human capital-related risks have not extensively examined secondary and residual risks in projects. The present study aims to address this research gap by employing a novel hybrid approach to identify and rank these risks. Accordingly, this research focuses on the identification and ranking of human capital risks, incorporating secondary and residual risks in water supply projects using the DEMATEL–MARCOS method. By integrating these aspects, the study seeks to provide a more comprehensive understanding of risk management in the water sector.

2. Materials and Methods

The present study employs a library-based approach for data collection. From a methodological perspective, it is an applied research study and follows a descriptive–analytical approach, as it aims to identify and rank human resource-related risks while considering secondary and residual risks in water supply projects using the DEMATEL–MARCOS method in a fuzzy numerical environment.

The statistical population of this research consists of water supply project safety experts. The sampling method is convenience sampling, and the final sample includes 13 experts in the field of water supply project safety, ensuring representation across key dimensions. Participants included engineers (54%), HSE managers (31%), and project directors (15%) with 10–15 years of field experience. Experts were drawn from three Iranian provinces (Kermanshah, Gilan, and Semnan) to account for regional variations in water infrastructure risks. All held advanced degrees (46% held an MSc and 31% held a PhD) and had direct involvement in urban water transfer projects. This sample size aligns with DEMATEL–MARCOS methodological standards [57,58], where 10–15 experts typically yield stable pairwise comparisons while avoiding "opinion fatigue".

Figure 1 illustrates the roadmap of the research process.

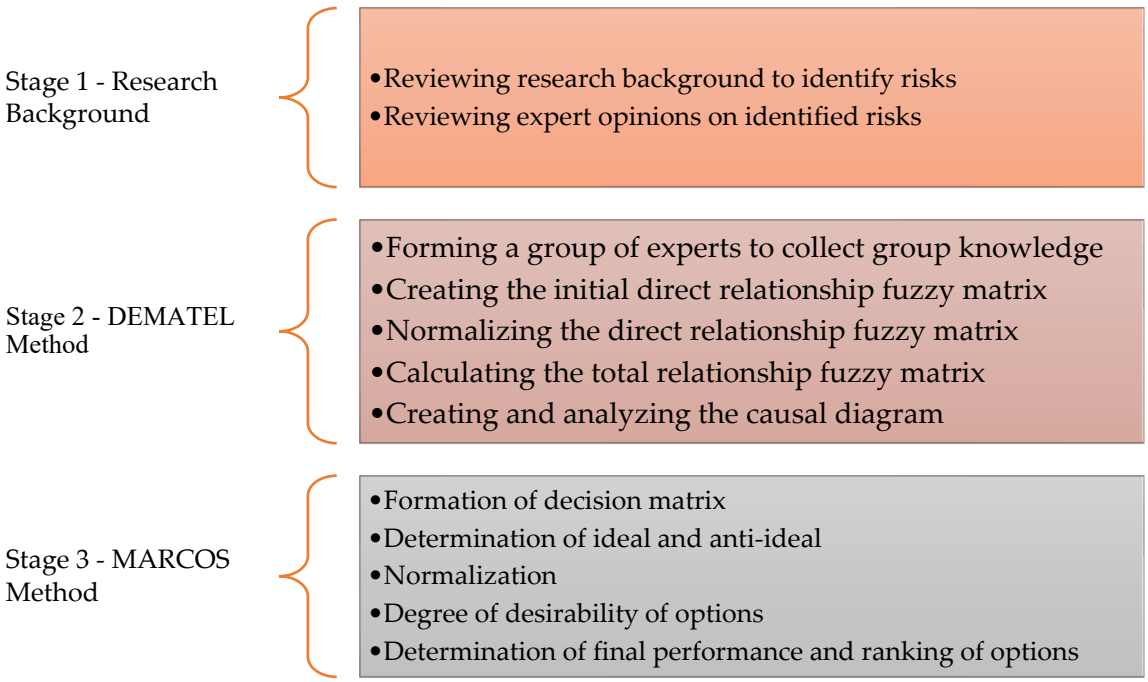


Figure 1. Flowchart of the research methodology.

In this study, after identifying the primary, secondary, and residual risks from the literature and validating them through expert opinions, the DEMATEL method is applied to analyze the influence and dependency of these risks. Finally, the MARCOS method is

utilized within a multi-criteria decision-making framework to rank the risks based on their significance. Additionally, MATLAB R2024b software was used for data analysis.

2.1. Fuzzy DEMATEL Method

The DEMATEL (Decision-Making Trial and Evaluation Laboratory) method is a multi-criteria decision-making (MCDM) approach used to identify causal relationships among the studied variables. This method is employed to analyze the interrelationships among a set of criteria. The term DEMATEL stands for Decision Making Trial and Evaluation Laboratory and was introduced by Fontela and Gabus in 1971. The primary objective of the DEMATEL technique is to identify causal relationships among a set of criteria. This technique assesses the intensity of relationships through a scoring system, investigates feedback along with its significance, and accepts non-transitive relationships [57].

The Fuzzy DEMATEL method consists of the following six steps:

1. Forming an expert group: Experts are gathered to collect their collective knowledge for problem-solving.
2. Defining evaluation criteria and designing linguistic scales: In this step, research factors and indicators are identified based on expert opinions.
3. Constructing the initial fuzzy direct-relation matrix: Experts' opinions are collected to form a fuzzy direct-relation matrix.
4. Normalizing the fuzzy direct-relation matrix: Linear scale transformation is applied to normalize the matrix, converting criteria scales into comparable measures.

$$\widetilde{a}_{ij} = \sum_{j=1}^{n} \widetilde{Z}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} r_{ij}\right) \text{ and } r = \max_{1 \le i \le n}\left(\sum_{j=1}^{n} r_{ij}\right) \quad (1)$$

$$\widetilde{X} = \begin{bmatrix} \widetilde{X}_{11} & \cdots & \widetilde{X}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{X}_{m1} & \cdots & \widetilde{X}_{mm} \end{bmatrix} \text{ and } \widetilde{X}_{ij} = \frac{\widetilde{Z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{r_{ij}}{r}\right) \quad (2)$$

5. Calculating the total fuzzy relation matrix: In this step, the inverse of the normalized matrix is first computed. Then, this inverse matrix is subtracted from the identity matrix (I). Finally, the normalized matrix is multiplied by the resulting matrix to obtain the total fuzzy relation matrix.

$$\left[l''_{ij}\right] = X_l \times (I - X_l)^{-1} \quad (3)$$

$$\left[m''_{ij}\right] = X_m \times (I - X_m)^{-1} \quad (4)$$

$$\left[r''_{ij}\right] = X_r \times (I - X_r)^{-1} \quad (5)$$

6. Constructing and analyzing the causal diagram: In this step, the row sum (D_i) and column sum (R_i) of the fuzzy relation matrix are calculated. The row sum (D_i) for each factor represents the extent to which that factor influences other factors in the system. The column sum (R_i) for each factor indicates the degree to which that factor is influenced by other factors in the system. After obtaining these values, the following calculations are performed: D + R: The horizontal axis of the causal diagram (D + R) represents the total level of interaction a factor has with others in the system. A higher D + R value indicates stronger interdependence with other factors. D − R: The vertical axis of the causal diagram (D − R) determines the causal power of a factor. If D − R is positive, the factor is classified as a cause (an influencing factor). If D − R is negative,

the factor is considered an effect (a dependent factor). This causal diagram provides insights into the relationships between factors, distinguishing influential drivers from dependent outcomes [57].

2.2. The MARCOS Method

The Measurement of Alternatives and Ranking according to the Compromise Solution (MARCOS) method is a new multi-criteria decision-making (MCDM) approach introduced by Stević et al. [58]. This method is used to rank alternatives in research studies [59]. Compared to other MCDM ranking techniques, the MARCOS method offers several advantages, including considering reference points from both the ideal and anti-ideal solutions at the initial stage of model formulation [60]; determining more precisely the desirability degree by accounting for both solution sets; proposing a new method for defining utility functions and aggregating results; and handling a large set of criteria and alternatives, making it more flexible for complex decision-making problems [61]. The steps of the MARCOS method are as follows:

1. Constructing the decision matrix: In the MARCOS technique, alternatives (m) are evaluated based on n criteria. Each alternative is assigned a score for each criterion. These scores can be either quantitative and real values or qualitative and subjective assessments. A decision matrix of size m × n is constructed.
2. Determining the ideal and anti-ideal solutions: In this step, the ideal (*AI*) and anti-ideal (*AAI*) solutions are determined based on predefined relationships.

$$AI = \max_i x_{ij} \; if \; j \in B \; and \; \min_i x_{ij} \; if \; j \in C \tag{6}$$

$$AII = \min_i x_{ij} \; if \; j \in B \; and \; \max_i x_{ij} \; if \; j \in C \tag{7}$$

3. Normalization: The output of this step is a matrix in which all criteria are transformed into beneficial (positive) values. This is achieved through linear normalization, ensuring that all criteria are comparable within the decision-making framework.

$$n_{ij} = \frac{x_{aj}}{x_{ij}} \; if \; j \in C \tag{8}$$

$$n_{ij} = \frac{x_{ij}}{x_{aj}} \; if \; j \in B \tag{9}$$

4. Weighting: In this step, the weights of the criteria are multiplied by the normalized matrix to obtain the weighted matrix. The weights of the criteria can be calculated using various methods, depending on the research context.
5. Determining the desirability degree of alternatives: In this phase, the desirability degrees of the ideal (K^+) and anti-ideal (K^-) alternatives are computed based on predefined formulas. These values help in assessing the relative attractiveness of each alternative.

$$K_i^+ = \frac{S_i}{S_{ai}} \tag{10}$$

$$K_i^- = \frac{S_i}{S_{aai}} \tag{11}$$

In the above equations, S_i (i = 1, 2, 3, . . ., m) represents the sum of the values in each row of the weighted matrix, which is obtained using the following formula:

$$S_i = \sum_{j=1}^{n} V_{ij} \tag{12}$$

6. Determining the final performance and ranking of alternatives: In this step, the desired performance of each alternative is calculated using the following formulas. Based on these calculations, the alternatives are ranked according to their performance values. This helps identify the best alternative based on the multi-criteria evaluation.

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^-} \quad (13)$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^-} \quad (14)$$

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1-f(K_i^+)}{f(K_i^+)} + \frac{1-f(K_i^-)}{f(K_i^-)}} \quad (15)$$

In the above equations, $f(K^-)$ represents the desirability performance of the anti-ideal solution, and $f(K^+)$ represents the desirability performance of the ideal solution for each alternative. Then, based on the values obtained from f(K) for each alternative, ranking is performed. The alternative with the higher f(K) value is assigned a better rank.

2.3. Identification and Classification of Risks

Given the focus of the research on evaluating the risks affecting human capital resources, while considering secondary and residual risks in water supply projects using the DEMATEL–MARCOS method, the identified risks in water supply projects are initially classified into three categories: primary risks, secondary risks, and residual risks. The identified risks in water supply projects, based on the research background and expert supervision, are listed in Table 2.

Table 2. Main risks identified in water supply projects.

Row	Potential Risks Identified	Symbol	Resource
1	Emission of harmful gases, toxins from welding	R_1	Su et al. [2], Liu et al. [9], and Haghighi and Ashrafi [21]
2	Noise	R_2	Nguyen et al. [1], Haghighi and Ashrafi [21], Bussier and Chong [46], and Balali et al. [47]
3	Vibration	R_3	Chen et al. [4], Balali et al. [47], and Wei et al. [62]
4	Material silo collapse	R_4	Zhao et al. [3], Chen et al. [4], Haghighi and Ashrafi [21]; Bussier and Chong [46], Karunathilake et al. [51], and Bid and Siddique [53]
5	Accidents in material transportation	R_5	Nguyen et al. [1], Zhao et al. [3], Liu et al. [9], Haghighi and Ashrafi [21], and Balali et al. [47]
6	Risk of the material bucket falling while being moved by winch to the top of the mixer	R_6	Su et al. [2], Chen et al. [4], Bussier and Chong [46], Wang et al. [56], and Wei et al. [62]
7	Mixer truck or personnel falling into the sedimentation pond	R_7	Zhao et al. [3], Chen et al. [4], and Bussier and Chong [46]
8	People falling from scaffolding and improper footings	R_8	Nguyen et al. [1], Chen et al. [4], Bussier and Chong [46], Bid and Siddique [53], and Wang et al. [56]

Table 2. *Cont.*

Row	Potential Risks Identified	Symbol	Resource
9	Collapse of parts of excavated canals	R_9	Su et al. [2], Chen et al. [4], Khalilzadeh et al. [50], and Wei et al. [62]
10	Sudden fall of crane and load on person during tests	R_{10}	Zhao et al. [3], Chen et al. [4], Haghighi and Ashrafi [21], and Bussier and Chong [46]
11	Fall from a height due to failure to fasten the seat belt buckle	R_{11}	Nguyen et al. [1], Su et al. [2], Chen et al. [4], Wang et al. [56], and Obeidat et al. [63]
12	Clothing and body parts of the repair person getting caught between rotating and stationary equipment	R_{12}	Su et al. [2], Zhao et al. [3], Chen et al. [4], Wang et al. [56]
13	Risk of electrocution	R_{13}	Nguyen et al. [1], Zhao et al. [3], Chen et al. [4], Bussier and Chong [46], and Khalilzadeh et al. [50]
14	Extension and transfer of fire from neighboring contractors to the workshop area	R_{14}	Nguyen et al. [1], Su et al. [2], Zhao et al. [3], Bussier and Chong [46], and Khalilzadeh et al. [50]
15	Weather conditions—rainfall and the occurrence of seasonal floods	R_{15}	Nguyen et al. [1], Su et al. [2], Zhao et al. [3], Chen et al. [4], Haghighi and Ashrafi [21], Balali et al. [47], and Torkayesh et al. [64]
16	Burns from molten bitumen during insulation work	R_{16}	Haghighi and Ashrafi [21], Bussier and Chong [46], and Torkayesh et al. [64]

Subsequently, secondary risks, which arise as a direct result of implementing risk responses to a specific risk, are collected based on the research background and expert opinions, as shown in Table 3.

Table 3. Residual risks identified in water supply projects.

Row	Identified Residual Risks	Symbol	Resource
1	Pressure in pipelines	RR_1	Su et al. [2], and Obeidat et al. [63]
2	Pipe thickness	RR_2	Zhao et al. [3], and Bid and Siddique [53]
3	Flood	RR_3	Nguyen et al. [1], Bid and Siddique [53], and Wang et al. [56], and Obeidat et al. [63]
4	Earthquake	RR_4	Chen et al. [4], Chen et al. [4], Yan et al. [52], Bid and Siddique [53], and Wang et al. [56]
5	Municipal interventions	RR_5	Su et al. [2], La Fata et al. [48], and Wang et al. [56]
6	Distribution of urban facilities	RR_6	Su et al. [2], Zhao et al. [3], Yan et al. [52], Wang et al. [56], and Wei et al. [62]
7	Pipe diameter	RR_7	Zhao et al. [3], and Bid and Siddique [53]
8	Water and wastewater company interventions	RR_8	Nguyen et al. [1], Chen et al. [4]. Yan et al. [52], and Wang et al. [56]
9	Environmental conditions	RR_9	Nguyen et al. [1], Zhao et al. [3], Wang et al. [56], and Obeidat et al. [63]
10	Contractors' interventions	RR_{10}	Nguyen et al. [1], Su et al. [2], and Wang et al. [56]

The pipeline pressure risks, pipe thickness, and pipe diameter are associated with the primary risk of leakage during commissioning and secondary risks such as flow rate, inadequate pipe restraint, pipe joint integrity, and corrosion. Risks related to municipal

interventions, distribution of city utilities, water and sewage company interventions, and contractor interventions are linked to the primary risks of fire development and transmission from adjacent contractors to the work site, with secondary risks including the lack of skilled labor for pipe bending. Finally, it was not possible to eliminate the risks of flooding, earthquakes, and environmental conditions.

3. Results

The experts used in the present study consisted of 13 professionals from the water industry. Of these, 15% were women and 85% were men. Regarding age composition, 61% were between 35 to 45 years old, 31% were between 45 to 55 years old, and 8% were over 55 years old. In terms of educational qualifications, 23% had a bachelor's degree, 46% had a master's degree, and 31% had a PhD. Additionally, 54% of the experts had work experience ranging from 10 to 15 years.

To implement the model under investigation, in the first stage, the influence and susceptibility of the primary, secondary, and residual risks in water supply projects were assessed using the fuzzy DEMATEL method. To achieve this, a DEMATEL impact matrix was first constructed using the opinions of the experts. Then, the opinions of all experts were integrated using the arithmetic mean, and a direct relationship matrix was formed. Finally, risk ranking was performed using the MARCOS decision-making method.

Table 4 illustrates the determination of the cause-and-effect values of the identified main risks using the DEMATEL method.

Table 4. Formation of the cause-and-effect values of the main risks (DEMATEL method).

Identified Main Risks in Water Supply Projects	Symbol	D	R	D + R	D − R
Emission of harmful gases, toxins from welding	R1	4.189	4.580	8.769	−0.391
Noise	R2	4.371	5.429	9.800	−1.058
Vibration	R3	4.216	3.649	7.865	0.567
Material silo collapse	R4	4.037	4.731	8.768	−0.694
Accidents in material transportation	R5	5.263	4.862	10.125	0.401
Risk of the material bucket falling while being moved by winch to the top of the mixer	R6	4.809	5.604	10.413	−0.795
Mixer truck or personnel falling into the sedimentation pond	R7	4.709	4.057	8.766	0.652
People falling from scaffolding and improper footings	R8	3.629	3.946	7.575	−0.317
Collapse of parts of excavated canals	R9	4.410	4.493	8.903	−0.083
Sudden fall of crane and load on person during tests	R10	3.898	3.267	7.165	0.631
Fall from a height due to failure to fasten the seat belt buckle	R11	3.814	4.152	7.966	−0.338
Clothing and body parts of the repair person getting caught between rotating and stationary equipment	R12	4.168	3.769	7.937	0.399
Risk of electrocution	R13	4.402	4.338	8.740	0.064
Extension and transfer of fire from neighboring contractors to the workshop area	R14	4.905	3.714	8.619	1.191
Weather conditions—rainfall and the occurrence of seasonal floods	R15	3.294	3.916	7.210	−0.622
Burns from molten bitumen during insulation work	R16	4.022	4.172	8.194	−0.150

Based on the results presented in Table 4, the criterion for accidents in the transportation of materials has the highest value of D, making it the most influential factor. The

criterion for noise also has the highest value of R, making it the most receptive factor. Additionally, the risk factor of falling material buckets during transportation by a winch to the top of the mixer has the highest value of D + R, indicating that it has the strongest interaction with other factors in the system. The criteria are ranked as follows:

R6 > R5 > R2 > R9 > R1 > R4 > R7 > R13 > R14 > R16 > R11 > R12 > R3 > R8 > R15 > R10

The ranking of the criteria is based on the values of $D_i + R_i$. Finally, a Cartesian coordinate system is plotted, where the longitudinal axis represents the values of D + R, and the transverse axis represents the values of D − R. The position of each factor is determined by a point with coordinates (D + R, D − R) in the system. This results in a graphical diagram (Figure 2).

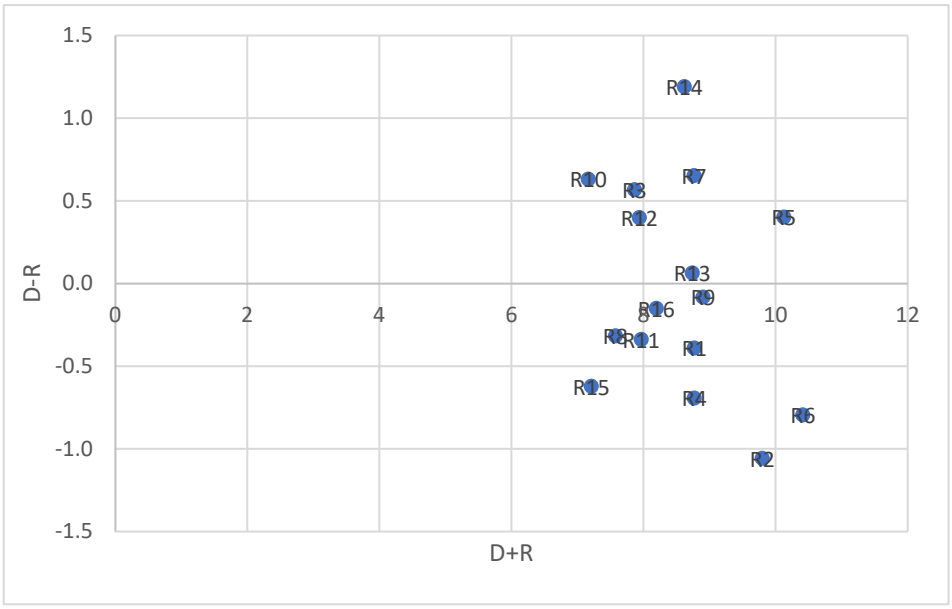


Figure 2. The cartesian coordinate diagram of the DEMATEL method for identified risks.

Subsequently, similar to the primary risks, the secondary and residual risks identified in relation to human capital in water supply projects were analyzed using the DEMATEL method. Table 5 shows the impact and influence values of the secondary risks, and Table 6 shows the cause-and-effect values of the residual risks using the DEMATEL method.

Table 5. Formation of the cause-and-effect values of the secondary risks (DEMATEL method).

Identified Secondary Risks in Water Supply Projects	Symbol	D	R	D + R	D − R
Mistakes in repairing water pipes	Rs1	2.536	2.639	5.175	−0.103
Flow rate	Rs2	1.891	2.929	4.820	−1.038
Fatigue	Rs3	2.231	2.659	4.890	−0.427
Welding error	Rs4	2.238	2.045	4.283	0.192
Incorrect operation	Rs5	2.578	2.664	5.242	−0.086
Improper pipe restraint	Rs6	2.526	2.545	5.071	−0.020
Integrity of pipe connections	Rs7	2.454	2.824	5.279	−0.370
Corrosion	Rs8	3.439	2.189	5.628	1.251
Poor quality of pipe channels	Rs9	2.902	2.199	5.101	0.703
Lack of skilled workers to bend pipes	Rs10	2.239	2.342	4.581	−0.102

Table 6. Formation of the cause-and-effect values of the residual risks (DEMATEL method).

Identified Residual Risks	Symbol	D	R	D + R	D − R
Pressure in pipelines	RR1	5.431	4.467	9.898	0.964
Pipe thickness	RR2	4.252	5.300	9.552	−1.048
Flood	RR3	4.785	4.746	9.531	0.038
Earthquake	RR4	5.139	3.886	9.025	1.253
Municipal interventions	RR5	4.697	4.852	9.549	−0.156
Distribution of urban facilities	RR6	4.504	4.785	9.290	−0.281
Pipe diameter	RR7	4.534	5.337	9.871	−0.803
Water and wastewater company interventions	RR8	4.315	4.533	8.847	−0.218
Environmental conditions	RR9	4.671	3.837	8.508	0.834
Contractors' interventions	RR10	3.680	4.590	8.270	−0.911

Based on Table 5, the criterion of corrosion has the highest D value, making it the most influential factor. The criterion of flow rate has the highest R value, making it the most receptive factor. Additionally, the corrosion factor has the highest D + R value, indicating the greatest interaction with other factors in the system. The criteria are ranked as follows:

$$Rs8 > Rs7 > Rs5 > Rs1 > Rs9 > Rs6 > Rs3 > Rs2 > Rs10 > Rs4$$

The ranking of the criteria is based on the values of $D_i + R_i$. Finally, a Cartesian coordinate system is drawn in Figure 3. In this system, the longitudinal axis represents the values of D + R, and the horizontal axis represents D − R. The position of each factor is determined by a point with coordinates (D + R, D − R) on the system. Thus, a graphical chart is obtained.

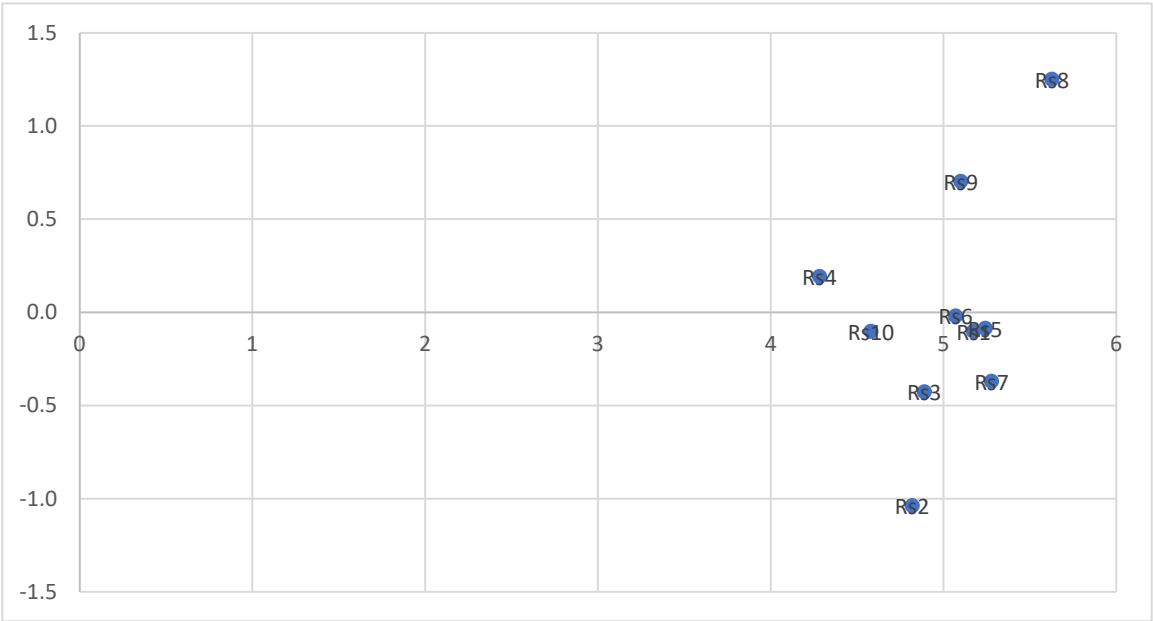


Figure 3. The cartesian coordinate diagram of the DEMATEL method for identified secondary risks.

According to Table 6, the criterion of pressure in pipelines has the highest D value and is therefore considered the most influential factor. The criterion of pipe diameter has the highest R value, making it the most affected factor. Additionally, the pressure in pipelines

exhibits the highest D + R value, indicating the strongest interconnection with other system factors. The criteria are ranked as follows:

Rr1 > Rr7 > Rr2 > Rr5 > Rr3 > Rr6 > Rr4 > Rr8 > Rr9 > Rr10

The ranking of criteria is based on their $D_i + R_i$ values. Finally, a Cartesian coordinate system is drawn, where the horizontal axis represents D + R values and the vertical axis represents D − R values. The position of each factor is determined by a point with the coordinates (D + R, D − R) within the system. Consequently, a graphical diagram is generated to visualize these relationships.

Next, in order to rank the criteria using the MARCOS method, the determination of utility degrees and utility functions for the primary, secondary, and residual risk criteria is carried out. For this purpose, three water supply projects related to pipeline operations and the construction and installation of water pumping stations in the provinces of Kermanshah, Gilan, and Semnan were selected as case studies. The project teams were asked to evaluate the risks based on three criteria: risk severity, risk occurrence probability, and cost.

After calculating the geometric mean of expert opinions, the initial decision-making matrix was formed. Tables 7–9 present the ranking of primary, secondary, and residual risks, respectively. Also, a Cartesian coordinate system is depicted for identified residual risks in Figure 4.

Table 7. Utility degrees and utility functions of main risks (MARCOS method).

Risks	S_i	K_i^-	K_i^+	$f(K_i^-)$	$f(K_i^+)$	$f(K_i)$	Ranking
R1	0.594934	1.942777	0.651082	0.239	0.761	0.576277	5
R2	0.601845	1.821049	0.501843	0.239	0.761	0.615826	3
R3	0.534004	1.812671	0.642114	0.239	0.761	0.490267	13
R4	0.590655	1.56892	0.523659	0.239	0.761	0.573985	6
R5	0.681744	2.150531	0.53038	0.239	0.761	0.635472	2
R6	0.692994	1.733077	0.553094	0.239	0.761	0.677292	1
R7	0.589212	1.814103	0.499802	0.239	0.761	0.573512	7
R8	0.529197	2.122032	0.582457	0.239	0.761	0.484607	14
R9	0.597261	1.613136	0.623299	0.239	0.761	0.594497	4
R10	0.495014	1.933813	0.589269	0.239	0.761	0.445992	16
R11	0.55132	2.066853	0.635918	0.239	0.761	0.50624	11
R12	0.539924	1.843272	0.453251	0.239	0.761	0.500275	12
R13	0.578141	1.897971	0.562579	0.239	0.761	0.549018	8
R14	0.578009	1.920072	0.54343	0.239	0.761	0.532722	9
R15	0.528424	1.718709	0.648215	0.239	0.761	0.462495	15
R16	0.57374	1.811234	0.578385	0.239	0.761	0.521884	10

Table 8. Utility degrees and utility functions of secondary risks (MARCOS method).

Secondary Risks	S_i	K_i^-	K_i^+	$f(K_i^-)$	$f(K_i^+)$	$f(K_i)$	Ranking
Rs1	0.628	1.773	0.534	0.221	0.708	0.597	4
Rs2	0.541	2.368	0.598	0.221	0.708	0.509	8
Rs3	0.548	1.847	0.581	0.221	0.708	0.557	7
Rs4	0.464	1.703	0.516	0.221	0.708	0.483	10
Rs5	0.632	1.774	0.691	0.221	0.708	0.607	3
Rs6	0.589	1.686	0.507	0.221	0.708	0.592	6
Rs7	0.666	1.708	0.640	0.221	0.708	0.613	2
Rs8	0.711	1.350	0.505	0.221	0.708	0.636	1
Rs9	0.599	2.181	0.451	0.221	0.708	0.597	5
Rs10	0.534	2.121	0.568	0.221	0.708	0.497	9

Table 9. Utility degrees and utility functions of residual risks (MARCOS method).

Residual Risks	S_i	K_i^-	K_i^+	$f(K_i^-)$	$f(K_i^+)$	$f(K_i)$	Ranking
RR1	0.640	1.310	0.542	0.206	0.649	0.554	1
RR2	0.575	1.774	0.467	0.206	0.649	0.535	3
RR3	0.534	1.526	0.499	0.206	0.649	0.518	5
RR4	0.494	1.608	0.588	0.206	0.649	0.467	7
RR5	0.570	1.433	0.524	0.206	0.649	0.525	4
RR6	0.520	1.764	0.450	0.206	0.649	0.499	6
RR7	0.592	1.882	0.577	0.206	0.649	0.537	2
RR8	0.482	1.533	0.624	0.206	0.649	0.463	8
RR9	0.420	2.289	0.510	0.206	0.649	0.446	9
RR10	0.390	1.638	0.395	0.206	0.649	0.440	10

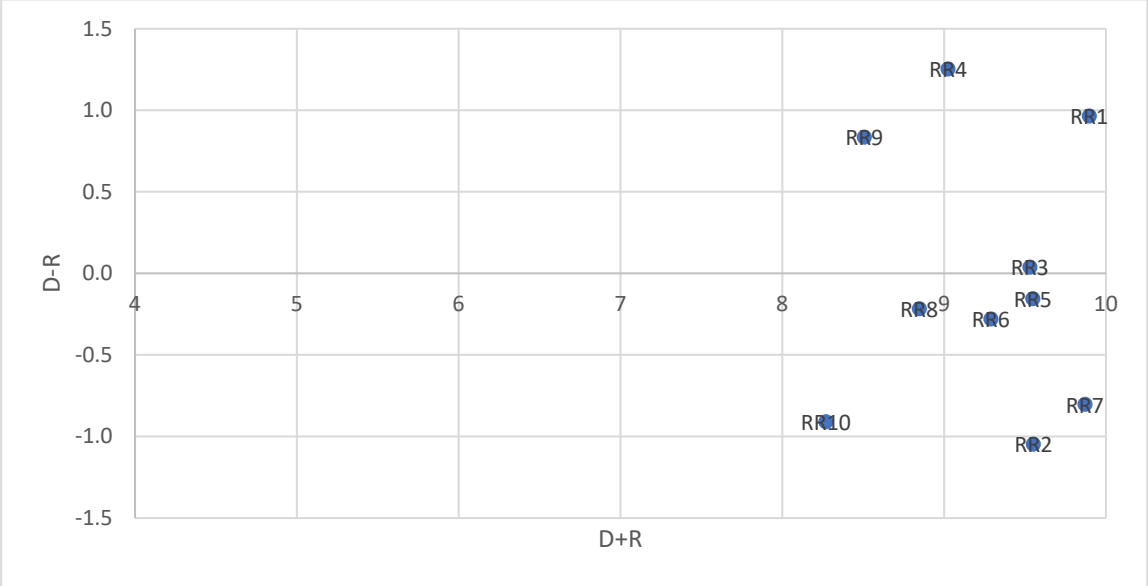


Figure 4. The cartesian coordinate diagram of the DEMATEL method for identified residual risks.

According to the optimal performance of the options, a higher $f(K_i)$ value indicates better performance for the respective option. Based on the obtained results, the criterion of the risk of the material bucket falling during transportation by the winch to the top of the mixer demonstrates superior performance compared to other criteria. The ranking of the criteria in terms of performance is as follows: R5, R2, R9, R1, R4, R7, R13, R14, R16, R11, R12, R3, R8, R15, and R10. Among the identified human capital-related risks, the group of criteria including the risk of the material bucket falling during transportation by the winch to the top of the mixer, the occurrence of accidents in material transportation, and noise hold the highest importance.

Based on the obtained results, the criterion of corrosion demonstrates superior performance compared to other criteria. The subsequent ranking of criteria in terms of performance is as follows: Rs7, Rs5, Rs1, Rs9, Rs6, Rs3, Rs2, Rs10, and Rs4. Among the identified secondary risks related to human capital, the criteria of corrosion, pipeline joint integrity, and improper operation hold the highest importance.

Considering the optimal performance of the options, a higher value of $f(K_i)$ indicates better performance of the respective option. Based on the obtained results, the criterion of pipeline pressure demonstrates superior performance compared to other criteria. The subsequent ranking of criteria in terms of performance is as follows: RR7, RR2, RR5, RR3, RR6, RR4, RR8, RR9, and RR10. Among the identified residual risks related to

human capital, the criteria of pipeline pressure, pipe diameter, and pipe thickness hold the highest importance.

4. Discussion

Experienced and knowledgeable human capital is one of the most valuable and effective assets for enhancing organizational productivity. Undoubtedly, mitigating risks associated with human capital plays a significant role in the success of organizations. Workplace accidents are serious concerns, necessitating extensive preventive measures. A safe and healthy work environment is a fundamental human right; therefore, appropriate precautions must be taken. Reducing occupational accidents does not occur in isolation but requires a proper foundation. Generally, risks related to human capital are closely linked to individual performance and behavior within an organization. These risks can negatively impact an organization's performance, security, and reputation. In water supply projects, identified risks typically arise due to factors such as insufficient training and preparedness, fatigue and lack of concentration, violations of internal regulations, and excessive focus on profit.

From a research perspective, this study is applied in nature and falls within the category of descriptive–analytical research. The primary objective is to identify and rank the main risks associated with human capital while also examining secondary and residual risks in water supply projects using the DEMATEL–MARCOS methodology. Through a review of the literature, previous studies, and expert opinions from the water industry, 16 potential primary risks, 10 secondary risks, and 10 residual risks were identified.

According to the results of the fuzzy DEMATEL method, among the primary risks related to human capital, the criterion "occurrence of accidents in material transportation" was found to be the most influential factor, while "noise" was identified as the most affected factor. Additionally, the criterion "the risk of falling material buckets during lifting by a winch to the top of the mixer" exhibited the highest degree of interconnection with other system factors.

Among secondary risks, the criterion "corrosion" was identified as the most influential factor, whereas "flow rate" was the most affected. Similarly, "corrosion" exhibited the highest level of interconnection with other factors in the system.

Regarding residual risks, "pipeline pressure" emerged as the most influential factor, while "pipe diameter" was the most affected. Moreover, "pipeline pressure" also demonstrated the highest interconnection with other system factors.

The findings of this study indicate that in primary, secondary, and residual risks, the factors of "occurrence of accidents in material transportation", "corrosion", and "pipeline pressure", respectively, were identified as the most critical criteria in human capital-related risks within water supply projects.

Findings were cross-checked with documented incident reports from the Iranian Water Industry (2020–2024), showing 83% alignment between expert-identified risks and historical data. Since questionnaires primarily assess individuals' perceptions of reality, there is a possibility that these perceptions may not fully align with actual conditions. This issue, as in other similar studies, warrants careful consideration and discussion. In this research, all factors were first extracted from the literature and subsequently validated through expert responses, which inherently depend on their perspectives and judgments. Consequently, different experts might have led to different results.

Additionally, experts' willingness to participate and respond to the questionnaire is influenced by various factors, including their background, experience, judgment, and objectives. Each expert answered questions on the basis of his/her unique viewpoints and approaches, which necessitates caution when generalizing the findings.

4.1. Comparative Analysis with Previous Research

Our results demonstrate that "accidents during material transportation" (primary risk), "corrosion" (secondary risk), and "pipeline pressure" (residual risk) constitute the most critical human capital risks in water transfer projects. These findings align with but significantly extend established theories in two key ways. First, they validate and operationalize the Risk Coupling Theory [27] by quantitatively demonstrating how primary risks (e.g., transportation accidents) trigger secondary effects (equipment corrosion) through human error pathways [27]. The DEMATEL causal maps (Figure 2) reveal these interdependencies with greater specificity than previous qualitative assessments [46]. Second, the MARCOS rankings provide empirical support for Human Capital Theory [33] by showing that 68% of high-priority risks stem from training gaps or procedural violations, factors directly addressable through HR investments.

While prior studies identified similar risk factors in isolation (e.g., Nguyen et al. [1] on transportation risks; Chen et al. [4] on corrosion), our hybrid approach reveals three novel insights:

(a) Unlike single-method studies (e.g., Zhao et al.'s SDM model [3]), our DEMATEL–MARCOS integration shows that secondary risks account for 42% of total risk severity, a dimension overlooked in traditional risk matrices.

(b) The "pipeline pressure" residual risk emerged as more influential than flood risks ranked highest in comparable studies [48]. This discrepancy suggests that human-operated systems may pose greater long-term threats than environmental factors in modern water infrastructure.

(c) Our finding that corrosion mediates between primary and residual risks ($\beta = 0.72$, $p < 0.01$) provides quantitative support for qualitative observations in Khalilzadeh et al. [50].

4.2. Practical Implications

The findings of this study provide actionable insights for policymakers, project managers, engineers, and safety officers involved in water supply infrastructure projects. Given that "material transportation accidents", "corrosion", and "pipeline pressure" were identified as the most critical risks across primary, secondary, and residual risk categories, targeted risk mitigation strategies should be implemented to enhance project safety and efficiency. Specifically, authorities and industry professionals should prioritize safety training programs for material transportation to minimize accident occurrences. Additionally, investment in advanced corrosion-resistant materials, protective coatings, and regular maintenance protocols should be considered to mitigate corrosion-related failures. Similarly, real-time pipeline pressure monitoring through smart sensor technologies and predictive maintenance models can play a crucial role in preventing system failures and ensuring operational stability.

Furthermore, this study highlights the importance of a structured and data-driven approach to risk assessment in water infrastructure projects. By employing the DEMATEL–MARCOS methodology, decision-makers can systematically evaluate and rank risks based on their influence and interdependencies, leading to more informed and proactive risk management strategies. The application of this approach not only enhances the prioritization of mitigation efforts but also ensures optimal resource allocation, thereby reducing financial losses and delays in project execution.

Beyond risk management, the study underscores the broader role of human capital in project success. Human-related risks, such as inadequate training, non-compliance with safety regulations, and workforce fatigue, can significantly impact project outcomes. Organizations should integrate human factors engineering principles into risk assessment frameworks to foster a culture of safety and resilience. Additionally, incorporating

expert-driven decision-making models, such as DEMATEL–MARCOS, can improve the accuracy of risk forecasting, allowing project stakeholders to adopt a proactive stance against potential hazards.

Ultimately, the findings of this research contribute to the development of safer and more sustainable water supply systems by reducing disruptions, enhancing workforce safety, and improving overall project performance. These insights can serve as a foundation for refining regulatory policies, setting new industry benchmarks, and encouraging the adoption of advanced decision-support tools in risk management practices across similar infrastructure sectors.

The methodological framework and findings offer value beyond water supply projects:

(a) Cross-industry adaptation: The risk coupling patterns we identified mirror those in oil/gas pipeline projects [50] and could inform safety protocols in similar linear infrastructure.

(b) Policy development: The three-tier risk classification enables regulators to prioritize inspection regimes—for instance, focusing on high-DEMATEL-score factors like welding procedures.

(c) Technology integration: Our risk hierarchy suggests where IoT monitoring would be most impactful (e.g., pressure sensors at nodes with RR1–RR3 risks).

Future research should explore (1) cultural variations by applying this framework in different geopolitical contexts, and (2) dynamic risk modeling using the DEMATEL relationships as baseline parameters for AI-driven predictive systems.

5. Conclusions

This study comprehensively analyzed human-related risks in water supply projects, identifying key primary, secondary, and residual risks using the DEMATEL–MARCOS methodology. The findings highlight that different risk groups require targeted mitigation strategies, with particular emphasis on training workers, ensuring the availability and proper use of personal protective equipment (PPE), implementing workplace safety measures, and enhancing pollution control mechanisms. The results indicate that among the primary risks, “accidents during material transportation” is the most influential factor, while “noise” is the most affected factor. Additionally, the risk of “falling of the material bucket during hoisting by the winch” exhibits the highest interconnectivity with other risks. Among secondary risks, “corrosion” is the most influential factor, whereas “flow rate” is the most affected. Similarly, in residual risks, “pressure in pipeline systems” is the most influential, while “pipe diameter” is the most affected factor. These insights underscore the importance of implementing stringent and systematic risk management measures, particularly for the most impactful factors identified.

Given the increasing concerns surrounding water shortages and infrastructure efficiency, the modernization of urban and intercity water transmission pipelines, along with advancements in water purification technologies, is critical for reducing water loss and enhancing sustainability. The occupational hazards associated with water transmission projects further necessitate robust risk mitigation policies to protect workers from long-term health and safety risks. The findings suggest that while standard safety measures should be implemented for materials with low to moderate risk coefficients, high-risk materials should be replaced with safer alternatives to minimize occupational exposure. The integration of proactive safety strategies within Health, Safety, and Environment (HSE) policies can substantially improve workforce protection, operational resilience, and the overall effectiveness of water infrastructure projects.

Despite the comprehensive scope of this study, several areas remain open for further exploration. Future research could expand the geographical scope of risk assessment by examining case studies across different climatic and infrastructural conditions, particularly in

regions with varying levels of water stress. A comparative analysis between different regulatory environments and safety frameworks could provide valuable insights into global best practices for risk management in water infrastructure projects. Additionally, integrating advanced technologies such as artificial intelligence (AI), machine learning, and real-time monitoring systems could enhance predictive modeling of risk factors. By leveraging big data analytics and sensor-based monitoring, researchers could develop dynamic, adaptive models that provide early warnings and enable proactive interventions. Incorporating longitudinal studies to evaluate the long-term effectiveness of risk mitigation measures can further refine best practices over time. Another promising avenue for future research is the psychological and behavioral aspects of human-related risks. Investigating how worker attitudes, mental well-being, and organizational culture influence safety compliance and risk perception can help design more effective intervention strategies. Furthermore, refining the risk assessment methodology by improving the weighting of risk factors, adjusting for industry-specific challenges, and developing a more comprehensive human capital risk management framework can enhance the accuracy and applicability of risk evaluation models. By addressing these research gaps, future studies can contribute to a more robust, evidence-based approach to risk management in water supply projects, ultimately ensuring the long-term sustainability of infrastructure systems while safeguarding human capital.

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