Water Resour Manage (2018) 32:4045–4061
https://doi.org/10.1007/s11269-018-2037-y

HHM- and RFRM-Based Water Resource System Risk Identification

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Received: 18 October 2017 / Accepted: 9 July 2018 /

Abstract In water resource system risk research, the risk identification problem should be addressed first, due to its significant impact on risk evaluation and management. Conventional risk identification methods are static and one-sided and are likely to induce problems such as ignored risk sources and ambiguous relationships among sub-systems. Hierarchical holographic modelling (HHM) and Risk filtering, ranking, and management (RFRM) were employed to identify the risk of water resources system. Firstly, water resource systems are divided into 11 major hierarchies and 39 graded holographic sub-subsystems by using the HHM framework. Iteration was applied on 4 graded holographic sub-subsystems, which were decomposed from water resource system in the time-space domain, to accurately identify 30 initial scenarios. Then, on the basis of RFRM theory, the risk probabilities of the initial scenarios are calculated and ranked, and 13 high risk scenarios are identified. Finally, the quantifiable 33 risk indicators

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that characterize the risk scenario are presented. Research results show that the risks affecting the water resources system include the composition, quantity, quality, and management of water resources, which involve many factors such as hydrology, human resources, resource allocation, and safety. Additionally, the study gives quantitative indicators for responding to high-risk scenarios to ensure that high-risk scenarios are addressed first, which is significant for the subsequent evaluation and management of water resource system risk.

Keywords Water resource system · Risk identification · HHM · Risk filter · Ranking

1 Introduction

Risks are always present in the natural environment and with regard to human activity. Risk assessment is crucial and involves four basic steps: risk identification, risk assessment, risk decision making and risk management. Of these topics, risk identification is the most important and the most challenging (Buytaert et al. 2012). If risk identification is limited to a one-sided, superficial understanding, then the quality of risk decision making is directly affected. Therefore, ignored risk sources lead not only to complete risk-management failure but also to larger losses (Liu and Shao 2005; Han et al. 2003).

Current risk identification methods include theoretical analysis methods (e.g., hierarchical decomposition and accident tree methods), expert investigation methods (e.g., the brainstorm and Delphi methods), scenario analysis methods, and the Monte Carlo method (Gong and Song 2010; Fei and Zou 2008; Feng and Wang 2003; Chen et al. 2010; Ando and Hynes 2016). In large-scale systems, hardware, software, and human factors are intertwined, and various sub-systems influence each other. Because the intrinsic properties of these systems affect risk-identification accuracy, it is difficult to capture a system's intrinsic properties via the aforementioned methods alone. Moreover, Large-scale complex systems have the following characteristics: immeasurable hierarchical goals, numerous decision makers, hierarchical and overlapping structures, and numerous risks and uncertainties. Hierarchical Holographic Modelling (HHM) is a comprehensive idea and methodology, the purpose of which is to capture and represent various intrinsic characteristics of a system. Most complex systems are essentially hierarchical, and the crux of HHM is to present a system framework via a hierarchical diagram. In a system with multiple interacting sub-systems, system hierarchical decomposition based on such a diagram is superior to conventional identification methods (Warfield 1978; Kaplan 2015; Haimes et al. 1986; He et al. 2013). As a complex and huge system, the water resources system has stratified and immeasurable characteristics. Therefore, the HHM system analysis also apply to water resources systems.

In addition, HHM theory recognises and supports the concept of complex systems; thus, an HHM framework is an effective and suitable risk-identification method for water resource systems and other large-scale complex problems (Staudinger et al. 2006; Haimes 2013; Isa et al. 2008; Shukla et al. 2011). The aim of this paper is to identify water resource risks and create a water resource risk evaluation index system. First, a water resource system undergoes time-space decomposition based on the operational process. This is then combined with the water resource system HHM framework to identify initial scenarios of water resource system risk. Next, the initial scenarios are filtered by three major constraints to form primary risk scenarios. Dual criteria are then applied to the primary scenarios for risk ranking and filtering to form secondary scenarios for prioritisation. Finally, multiple criteria and the Bayes formula are applied to the secondary scenarios for filtering, quantitative grading and ranking to identify the high-risk scenarios and the risk representation index and provide a comprehensive index system for subsequent water resource system risk evaluation and management.

2 Methods

2.1 Risk Definition

Kaplan and Garrick provided the following “3-tuple” risk definition (Perry and Herd 2004; Kaplan and Garrick 1981):

$$R = \{(S_i, L_i, X_i)\}_c \tag{1}$$

where S_i represents the ith risk scenario; L_i represents the likelihood of the ith risk scenario; X_i represents the loss vector or consequence of the ith risk scenario; and c denotes that risk scenario S_i is complete (i.e., it includes all possible risk scenarios or at least all significant risk scenarios).

This risk definition shows that the function of risk identification is to identify the risk scenario of the object under evaluation. The completeness of the risk scenarios determines the accuracy and reliability of the risk assessment result. Therefore, risk scenario identification is the most important step in risk evaluation. In this paper, a water resource system is decomposed via the HHM framework and combined with water resource system operation processes to identify risk scenarios. At the same time, the probability and consequence of risk scenario occurrence are processed using risk filtering, ranking and management (RFRM).

2.2 Overview of the HHM Framework Theory

Risk is related not only to the system itself but also to variation in many aspects of society (e.g., functionality, environment, and law). In system modelling and risk identification, HHM can be used to create a comprehensive theoretical framework for the entire system. The HHM method is primarily employed in risk identification for multidimensional and complex systems. Currently, HHM is widely adopted in risk identification for space missions, terrorism, aircraft development, information intelligence, etc. (Arquilla and Ronfeldt 2001; Brown and Lall 2006; Paté-Cornell and Fischbeck 1994) Water resource systems represent major social support systems and their diversity, and complexity cannot be described by a single model. The HHM framework provides a comprehensive approach to water resource systems, linking them closely with society.

Water resource systems are complex, involving multiple disciplines. To ensure the comprehensive nature of the water resource system HHM framework, in this paper, based on the analysis of basic attributes (hydrologic characteristics, quantity and quality) and social attributes (ecology, law and management) related to water resources, water resource systems are divided into 11 major hierarchies, including hardware, hydrological characteristics, surface water, ground water, and others, with each major hierarchy representing a different risk angle. To improve the validity and comprehensiveness of the water resource system HHM framework-based identification, a representative graded holographic sub-system should be selected for each angle. In this paper, the 11 major hierarchies are subdivided into 39 graded holographic sub-subsystems to form the water resource system HHM framework (Fig. 1). As a society develops, its sources of water resource system risk increase accordingly. Therefore, the HHM framework is extended accordingly to ensure the accuracy and comprehensiveness of water resource system risk identification. Additionally, the extensibility of the HHM framework is an advantage of this approach.

Individual angle may not be risky, but the interaction between different risk angles may make a certain angle risky. Therefore, each angle needs to be iterated with other angles. Water resource system risk determination using the HHM framework-based recurrent iteration involves performing iterations for 11 major hierarchies in pairs and identifying a series of scenarios. This type of iteration process generates an unfiltered original scenario, which then undergoes risk filtering, ranking and management (RFRM) to identify the water resource system risk. Iteration processes for major hierarchies such as "hardware" and "quantity" are used as examples, and the "A_1 pipe" holographic sub-system is used as an example to calculate its correlation with 6 other holographic sub-systems in the "hardware" and "quantity" categories. For example, the iteration process for "A_1 pipe" and "F_1 meteorological factor" is as follows: in a frigid zone, temperature and atmospheric-pressure-induced problems such as a reduced water pipe safety coefficient, unsteady water delivery and evaporation of poisonous substances lead to a certain level of risk in the water resource system. Consequently, the iteration process for the "A_1 pipe" and the "F_1 meteorological factor" holographic sub-systems has identified risk to the water resource system, and therefore, an initial risk scenario is formed. Similarly, iterations of holographic sub-systems under different angles generate more initial scenarios to ensure all initial scenarios are identified (Fig. 2).

2.3 Water Resource System Time-Space Division

2.3.1 Water Resource System Time-Space Decomposition

In risk evaluation and management, an HHM framework is employed to identify risk scenarios. These risk scenarios originate from a multi-layer overlapping structure of actual systems and extend these layers. A water resource system is decomposed based on the flow direction of risk, and HHM frameworks for different processes are consolidated. This method helps handle the complexity among the various risk factors as well as ensures a typical and comprehensive water resource system risk identification procedure (Haimes 2007; Essen et al. 2009).

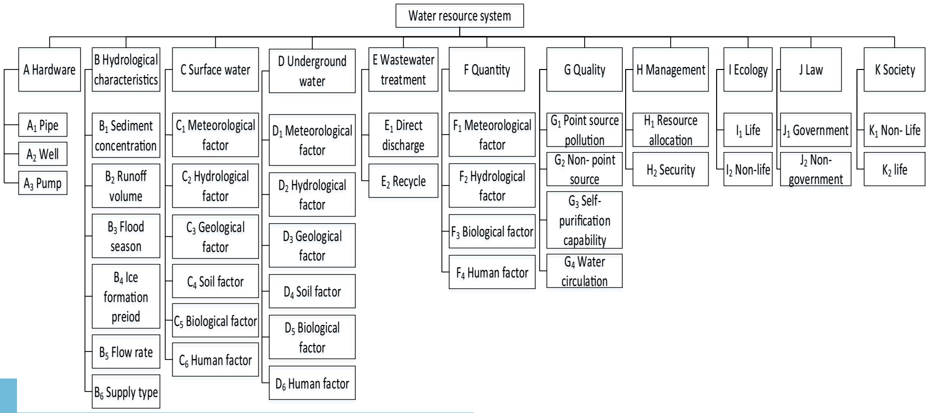


Fig. 1 Water resource system HHM framework

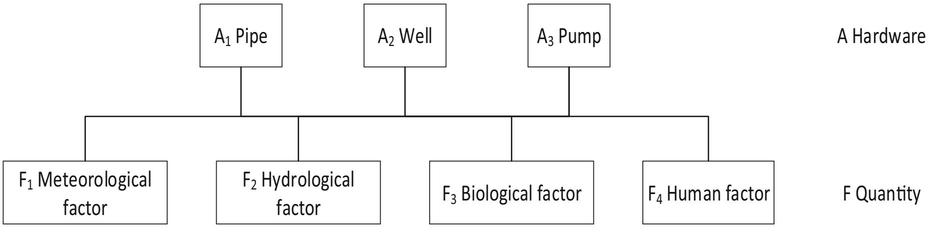
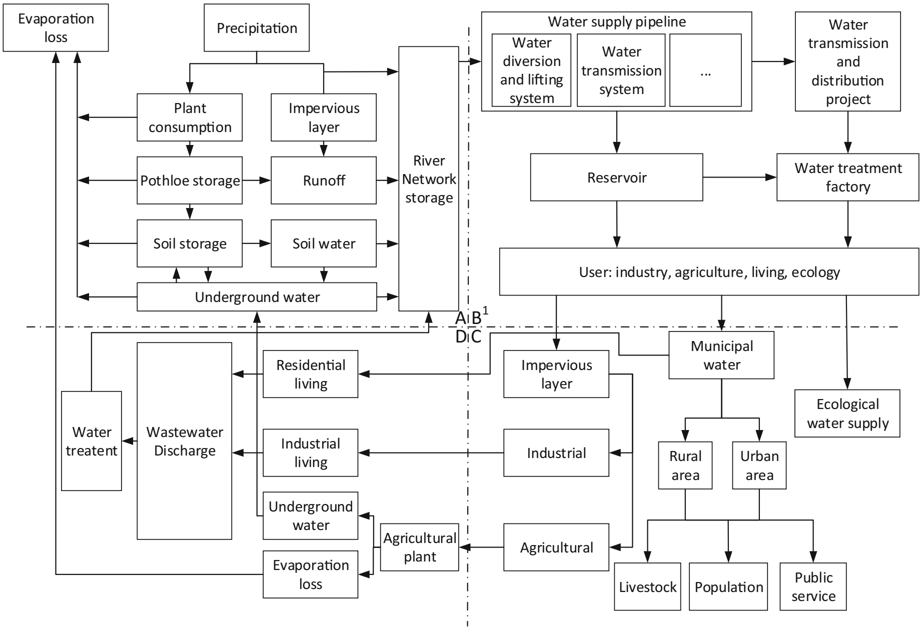


Fig. 2 The iteration process for hardware and quantity angles

In water resource systems, the water resource use process starts with precipitation and ends with human activity. Therefore, a water resource system operation is divided by time and space into four processes that include the natural feed, resource supply, resource use, and resource recycling (Fig. 3).

The natural feed process is the source of water resource formation in which precipitation eventually creates surface water and groundwater through various channels, including runoff and soil infiltration. The water resource supply process may include water storage, diversion, and lifting. The resource use process is a distribution process in which water resources are distributed to production, residential, and ecological users with different water quantity and quality requirements for different sectors (Agathokleous et al. 2017). The resource recycling process is the process of water resource recycling. Water for living and production is utilised and discharged as sewage. After treatment and cleaning, the water is recycled. After agricultural plant irrigation, some water returns to nature via evaporation, while other water seeps through the soil to become groundwater.



[1]A is the natural feed process; B is the resource supply process; C is the resource use process; D is the resource recycling process.

Fig. 3 Water resource system time-space decomposition

2.3.2 Constraints on Water Resource Systems

Natural and human factors affect the quality and quantity of water resources. Urban economic development planning and geological conditions also constrain water project deployment. Therefore, water resource system risks should be determined under the constraints of the economy as well as time and space.

According to the overall development plan and the coordinated regional industry development roadmap in China, the total investment in a water resource system is not a fixed value; rather, it is designed by the government based on an overall plan. Therefore, the risk identification process seeks to make reasonable identifications based on GDP. The current research defines the proportion of hydraulic construction investment to the total construction investment in China as the economic constraint index.

A time constraint refers to the uncertainty in precipitation and river runoff processes over time. Runoff volume, supply type, sediment concentration, and ice formation period durations vary with the season and the year. This research uses parameters such as precipitation, the runoff variation coefficient, and the non-uniformity coefficient as time constraint indices.

As urbanisation, modernisation, informatisation, and industrialisation progress steadily throughout the world, hydraulic project requirements become more complex. To accommodate new society types, space constraints are imposed. This paper uses the urbanisation ratio and the industrialisation level as space constraint indices.

2.4 The RFRM Model

Water resource systems include complex processes and many risks. In addition, the economic and social resources allocated for a water resource system are limited. Therefore, risks with significant effects on water resource systems should be screened for control. RFRM seeks to determine the risk factor ranking via water resource system risk scenario analyses. In this paper, based on the RFRM theory, initial scenarios identified by the HHM framework undergo filtering, dual criteria evaluation, multiple criteria evaluation and quantitative management, a comprehensive water resource system risk filtering process. Quantitative ranking and scenario indices are employed to identify high risks in water resource systems and the corresponding quantitative indices.

The RFRM model is composed of six phases (Zhang and Xiao 2011). For details, see Table 1.

(1) Scenario identification: HHM can be used to identify most risk sources to form an initial scenario for a water resource system. This scenario is the fundamental scenario in an RFRM model and should be the focus.

(2) Scenario filtering: It is impossible to immediately address many risks and risk sources. During this phase, the primary goal is to reduce the number of initial scenarios based on actual water resource use and three major constraints.

(3) Dual criteria filtering and ranking: In this stage, a dual-criteria filtering and ranking matrix is employed to filter minor risks. This matrix classifies risks into five grades based on probability and consequence. The risk probability is provided based on relevant research (Song and Hongtao 2013) (Table 2). When the risk probability is higher and the consequences are more severe, the risk grade is higher. After dual criteria filtering and ranking, risk scenarios with high probability and severe consequences at the top right corner of Table 2 are preserved.

Table 1 RFRM phases

No.	Phase	Description
1	Scenario identification	Recurrent iteration of major hierarchy in HHM framework to identify initial scenario
2	Scenario filtering	Initial scenario filtering via three major constraints to form a primary risk scenario
3	Dual criteria filtering and ranking	Primary risk scenario filtering via risk likelihood and consequences to form a secondary risk scenario
4	Multi-criteria assessment	Secondary risk scenario multi-criteria assessment based on the four major characteristics of water resource system risk
5	Quantitative ranking	Secondary risk scenario filtering and ranking based on quantitative and qualitative matrices for probabilities and consequences to form a high-risk scenario
6	Risk management	Proposal of typical evaluation index based on high-risk scenarios

(4) Multi-criteria assessment: After dual criteria filtering, prioritised risk scenarios are evaluated to determine the severity of the risk consequence. In this paper, the evaluation criteria are based on water resource system risk characteristics including risk probability, damage susceptibility, recoverability and risk grade.

(5) Quantitative ranking: The scenario probability is quantified based on Bayes' theorem (Mujumdar and Nirmala 2007; Said 2006) and historical data to form a quantitative ranking matrix, high- or relatively high-risk scenarios in the upper right area of Quantitative ranking matrix are identified to form a final risk scenario.

(6) Risk management: To address high-risk scenarios, this paper describes risk in the form of indices (i.e., the final risk scenario is described using one or more indices).

2.5 Research Approach

Based on an overview of research approaches, the research approach of HHM- and RFRM-based water resource risk identification is summarised in Fig. 4. The research procedure is as follows.

Step 1: The water resource system undergoes time-space decomposition to identify correlations between processes and risk sources for each process.

Step 2: The water resource system HHM framework and the water resource time-space decomposition are combined to identify risk sources via recurrent iteration, and the initial scenarios are identified.

Table 2 Dual criteria filtering and ranking matrix

Probability Consequence	Unlikely [0–0.01)	Low [0.01–0.03)	Occasional [0.03–0.06)	Likely [0.06–0.1)	Frequently [0.1–1]
A. Disastrous	high risk	high risk	high risk	high risk	high risk
B. Severe	medium risk	medium risk	relatively high risk	relatively high risk	high risk
C. Normal	low risk	medium risk	medium risk	relatively high risk	high risk
D. minor	low risk	low risk	low risk	medium risk	relatively high risk
E. Negligible	low risk	low risk	low risk	low risk	low risk

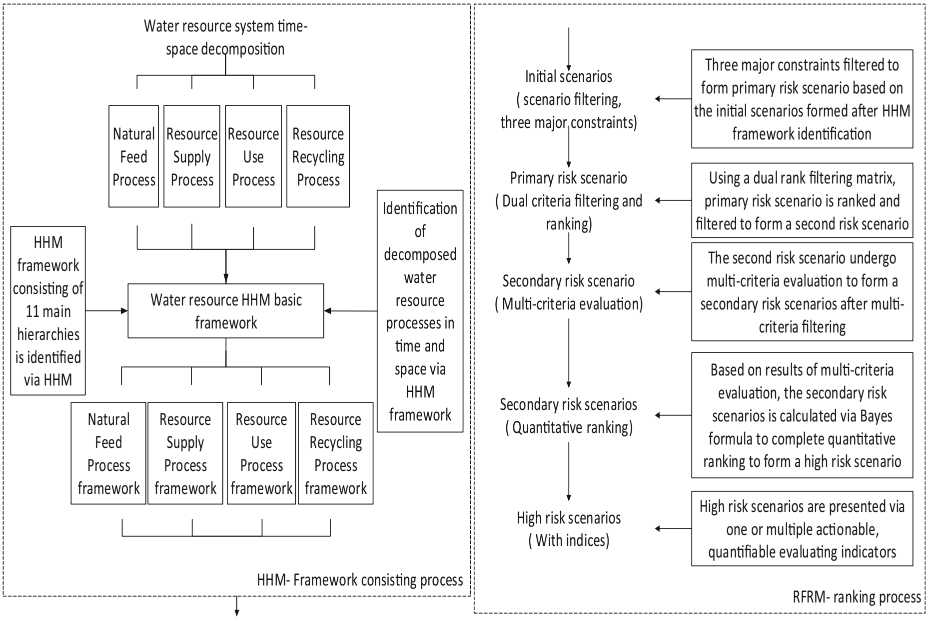


Fig. 4 Research approach

Step 3: The initial risk scenarios are filtered by three major constraints to form primary risk scenarios.

Step 4: Dual criteria filtering and a ranking matrix are employed to consolidate consequence severity and occurrence probability of the primary risk scenarios to form secondary risk scenarios.

Step 5: Multiple criteria evaluation and a quantitative ranking matrix are employed to eliminate low- and medium-risk scenarios from the secondary risk scenarios and identify high-risk scenarios using the quantitative Bayes formula.

Step 6: High-risk scenarios are represented via one or more quantitative and operable indices to obtain initial an index set for water resource system risk.

3 Results and Analysis

3.1 HHM-Framework-Based Water Resource System Identification

In water resource systems, the risk contained in the holographic sub-systems in each hierarchy was identified via the HHM framework, which helps to understand and evaluate the risk of the entire system. Because every process and risk in the water resource system affects others, a recurrent iteration method was employed to analyse the water resource system risk via an HHM framework (i.e., each risk viewpoint was compared with others to determine the interaction between them). Similarly, the water resource system was decomposed into four processes, and an HHM framework was employed for identification and analysis to obtain the risks for the four processes and generate 30 initial scenarios during the entire operation of the water resource system (Table 3).

Table 3 Initial scenarios

Major hierarchy	Natural feed process	Resource supply process	Resource use process	Resource recycling process	Entire process
A	A_1	A_1, A_2	-[a]	A_1	A_1, A_2
B	B_1, B_6	B_1, B_2	–	B_1, B_2	B_1, B_2, B_6
C	C_2, C_4, C_5, C_6	–	–	–	C_2, C_4, C_5, C_6
D	D_2, D_4, D_5, D_6	–	–	–	D_2, D_4, D_5, D_6
E	–	–	–	E_1, E_2	E_1, E_2
F	F_2, F_3, F_4	F_1, F_2, F_3, F_4	F_3, F_4	F_3, F_4	F_1, F_2, F_3, F_4
G	G_1, G_2	G_1, G_2	G_1, G_2	G_1, G_2, G_4	G_1, G_2, G_4
H	H_1, H_2	H_1, H_2	H_1, H_2	H_2	H_1, H_2
I	I_1, I_2	I_1, I_2	I_1, I_2	I_1, I_2	I_1, I_2
J	J_1, J_2	J_1, J_2	J_1, J_2	J_1, J_2	J_1, J_2
K	K_1, K_2	K_2	K_1, K_2	K_1, K_2	K_1, K_2
Total	24	17	12	17	30

[a] "-" represents a scenario with no risk

3.2 Risk Filtering and Ranking

After the HHM framework creation and pairwise iteration, a complete picture of the water resource system risk was obtained. Because of limited risk management resources, however, key risks should be highlighted. RFRM theory prioritises risk analyses so that critical risks are analysed first. In this paper, RFRM theory was employed for risk filtering and ranking to identify high-risk scenarios and construction of water resources system risk evaluation index system.

3.2.1 Scenario Filtering

Many risks cannot be addressed immediately at the source. Following the social effects, however, some evolve into high-risk scenarios with enormous risks. Therefore, scenario filtering highlights these risk scenarios to improve the important phase of risk identification. Three major constraints proposed in the previous sections were applied to filter the initial scenarios of the four processes to identify primary risk scenarios for each process that correspond with actual situations (Table 4).

Table 4 Primary risk scenarios

Major hierarchy	Resource feed process	Resource supply process	Resource use process	Resource recycling process	Entire process
A	-[a]	A_1, A_2	–	–	A_1, A_2
B	B_6	B_1, B_2	–	–	B_1, B_2, B_6
C	C_2, C_6	–	–	–	C_2, C_6
D	D_2, D_4, D_6	–	–	–	D_2, D_4, D_6
E	–	–	–	E_1	E_1
F	F_2, F_4	F_1, F_2, F_3, F_4	F_4	F_4	F_1, F_2, F_3, F_4
G	G_1, G_2	G_1, G_2	–	G_1, G_2	G_1, G_2
H	H_1, H_2	H_1, H_2	H_1, H_2	H_2	H_1, H_2
I	I_1, I_2	I_1, I_2	–	–	I_1, I_2
J	J_1, J_2	J_1, J_2	–	–	J_1, J_2
K	K_1, K_2	K_2	–	–	K_1, K_2
Total	18	17	3	5	25

[a] "-" represents a scenario with no risk

Finally, 25 primary risk scenarios for the entire water resource system operation were identified.

3.2.2 Dual Criteria Filtering and Ranking

Risk ranking was performed based on dual criteria filtering. A risk-ranking matrix was employed to filter risk scenarios with normal and low risks. Based on water resource system characteristics and actual situations, the risk probability and consequence are considered to perform dual criteria filtering and ranking for 4 water resource system processes. Finally, 20 risk scenarios are selected as secondary risk scenarios. The resource supply process was used as an example, and dual criteria were employed to remove A_2, F_1, J_1, F_3, J_2, B_2, and G_2 to form a set of secondary risk scenarios for this process (Table 5).

3.2.3 Multi-Criteria Assessment

After dual criteria assessment and filtering, the risk scenarios in the upper right area of the risk matrix were prioritised. However, the consequences and occurrence probabilities of water resource system risk scenarios are only direct evidence for a quantitative analysis, and limitations exist. For a specific risk scenario, the effect of a risk scenario on the water resource system should be investigated from multiple dimensions. In this paper, water resource system risk probability, damage susceptibility, recoverability and risk grade are employed to perform multiple criteria analysis and multi-dimension evaluation (Giordano et al. 2005; Ruan et al. 2005). The risk ratio refers to the ratio of normal water resource operational time to the entire operational time. Vulnerability is an important index to describe the average severity of water resource system failure loss. Recoverability describes the probability for a system to return to its normal state from an emergency state; higher system recoverability means that it takes less time for a system to return to its normal operational state from an emergency state. Risk likelihood is a mathematical characteristic of a probability distribution (standard deviation δ or semi-standard deviation δ^{-}),with larger values denoting higher levels of risk. In this paper, the risk ratio, vulnerability, recoverability, and risk likelihood were classified into three consequence grades via questionnaire and expert grading: high (H), normal (N), and low (L). The multi-criteria assessment results for the secondary risk scenarios are listed in Table 6.

3.2.4 Quantitative Ranking

During the quantitative ranking phase, the Bayes' theorem was introduced, and all available data were leveraged to quantify the probability of the risk scenario occurring. The quantification result was distributed across the quantitative risk ranking matrix, and scenarios with low or normal risks were removed.

Pipes (A_1) in the major hardware hierarchy are used as an example. Table 4 shows that the occurrence probability of risk scenario A1 in the water resource system is 3%. However, if this risk occurs, then its consequence is severity grade B. In following expression, x represents the consequence of pipe risk, and *e* represents a precautionary action taken by the decision-makers to mitigate the pipe risk scenario.

$$\Pr(x) = 0.3, \Pr\left(\overline{x}\right) = 0.7, \Pr(e|x) = 0.03, \Pr\left(e|\overline{x}\right) = 0.97$$

Table 5 Dual criteria filtering and the ranking matrix for the resource supply process

Probability Consequence	Impossible [0–0.01]			
	Low [0.01–0.03]	Occasional [0.03–0.06]	Likely [0.06–0.1]	Frequent [0.1–1]
A. Disastrous	H_2, I_1, I_2	F_2, H_1, K_2	F_4	
B. Severe	A_2, F_1, J_1	A_1, B_1	G_1	
C. Normal	F_3, J_2	B_2, G_2		
D. Minor				
E. Negligible				

Based on the total probability and the Bayes formula, we obtain

$$\Pr(e) = \Pr(x)\Pr(e|x) + \Pr\left(\overline{x}\right)\Pr\left(e|\overline{x}\right) \tag{2}$$

$$\Pr(x|e) = \frac{\Pr(x)\Pr(e|x)}{\Pr(e)} \tag{3}$$

Therefore, in the major hardware hierarchy, the posterior probability of the pipe (A_1) scenario is $\Pr(x|\,e) = 0.0131$. The posterior probabilities of other risk scenarios are calculated via the same method. Based on the range of the quantitative risk, all calculation results are listed in Tables 7 and 8 to create the quantitative risk ranking matrix.

Table 6 Multi-criteria assessment for secondary risk

Secondary risk scenario	Risk ratio	Vulnerability	Recoverability	Risk likelihood	Consequence		
					Grade	Range	Value
A_1	N	H	H	N	B	0.3–0.5	0.3
B_1	H	L	H	H	B	0.3–0.5	0.3
B_6	H	H	L	H	B	0.3–0.5	0.3
C_2	H	H	N	H	A	0.5–1	0.6
C_6	N	H	H	H	A	0.5–1	0.6
D_2	H	H	N	H	A	0.5–1	0.5
D_4	L	H	H	H	B	0.3–0.5	0.35
D_6	N	H	H	H	A	0.5–1	0.65
E_1	H	H	N	N	B	0.3–0.5	0.3
F_2^{+}[a]	H	H	H	H	A	0.5–1	0.65
F_4^{-}[b]	H	H	H	H	A	0.5–1	0.7
G_1^{*}[c]	L	H	H	H	B	0.3–0.5	0.3
G_2^{+}	H	H	H	H	A	0.5–1	0.65
H_1^{*}	N	H	H	H	A	0.5–1	0.55
H_2^{-}	H	H	H	H	A	0.5–1	0.6
I_1^{+}	H	H	H	H	A	0.5–1	0.55
I_2^{+}	H	H	H	H	A	0.5–1	0.6
J_1	L	H	H	H	B	0.3–0.5	0.4
K_1	H	H	N	H	B	0.3–0.5	0.3
K_2^{+}	H	H	H	H	A	0.5–1	0.6

[a] "+" denotes that this risk scenario occurs in two processes in the water resource time-space decomposition

[b] "-" denotes that this risk scenario occurs in four processes in the water resource time-space decomposition

[c] "*" denotes that this risk scenario occurs in three processes in the water resource time-space decomposition

Table 7 Risk probabilities calculated based on the Bayes formula

Risk scenario	$\Pr(x)$	$\Pr(\bar{x})$	$\Pr(e\mid x)$	$\Pr(e\mid\bar{x})$	$\Pr(e)$	$\Pr(x\mid e)$
A_1	0.3	0.7	0.03	0.97	0.688	0.0131
B_1	0.3	0.7	0.035	0.965	0.686	0.0153
B_6	0.3	0.7	0.06	0.94	0.676	0.0266
C_2	0.6	0.4	0.3	0.7	0.46	0.3913
C_6	0.6	0.4	0.5	0.5	0.5	0.6000
D_2	0.5	0.5	0.3	0.7	0.5	0.3000
D_4	0.35	0.65	0.06	0.94	0.632	0.0332
D_6	0.65	0.35	0.4	0.6	0.47	0.5532
E_1	0.3	0.7	0.06	0.94	0.676	0.0266
F_2^+	0.65	0.35	0.5	0.5	0.5	0.6500
F_4^-	0.7	0.3	0.1	0.9	0.34	0.2059
G_1^*	0.3	0.7	0.06	0.94	0.676	0.0266
G_2^+	0.65	0.35	0.03	0.97	0.359	0.0543
H_1^*	0.55	0.45	0.06	0.94	0.456	0.0724
H_2^-	0.6	0.4	0.08	0.92	0.416	0.1154
I_1^+	0.55	0.45	0.095	0.905	0.4595	0.1137
I_2^+	0.6	0.4	0.055	0.945	0.411	0.0803
J_1	0.4	0.6	0.01	0.99	0.598	0.0067
K_1	0.3	0.7	0.03	0.97	0.688	0.0131
K_2^+	0.6	0.4	0.5	0.5	0.5	0.6000

The quantitative risk-ranking matrix filtered out seven risk scenarios (J_1, A_1, B_1, B_6, K_1, E_1, and G_1) associated with normal risk and selected 13 other high-priority scenarios that had either high or relatively high risks to form a set of high-risk scenarios. High-priority scenarios include: C_2 (Hydrological factor) and C_6 (human factors) in surface water major hierarchy; D_2 (Hydrological factor), D_4 (soil factor) and D_6 (human factors) in underground water major hierarchy; F_2 (Hydrological factor) and F_6 (human factors) in quantity major hierarchy; G_2 (non- point source) in quality major hierarchy; H_1 (resource allocation) and H_2 (security) in Management major hierarchy; I_1 (life) and I_2 (non-life) in the ecological major hierarchy; K_2 (life) in the social major hierarchy. Among the 11 major hierarchies of the water resources system, the risks exist in 7 major hierarchies. The diversity of risk confirms that the water resources system is a complex system with multiple dimensions. Table 8 shows that there are 3 human factors and 3 hydrological factors in the 13 high risk scenarios. In the study, the human factors are important to the risk of water resources system, which coincides with the research direction of water resources system under the influence of human activities (Haddeland et al. 2014; Ghervase et al. 2012; Peng et al. 2014). Only under the premise of rational development

Table 8 Quantitative ranking matrix

Probability Consequence	Impossible [0–0.01]	Low [0.01–0.03]	Occasional [0.03–0.2]	Likely [0.2–0.5]	Frequent [0.5–1]
A. Disastrous			G_2, H_1, H_2, I_1, I_2	C_2, D_2, F_4	C_6, D_6, F_2, K_2
B. Severe	J_1	A_1, B_1, B_6, K_1, E_1, G_1	D_4		
C. Normal					
D. Minor					
E. Negligible					

and utilization of water resources can humans achieve a steady and healthy development of the water resources system so as to benefit humanity. Another important inducement that affects the risk of water resources system is hydrological factor. From action mechanism of the water resources system, the risk brought by hydrological factor is closely related to its own uncertainty. This uncertainty stems from the randomness and variability of the climate system, which leads to a series of risks such as increased flood hazards, irregular runoff and seasonal variations, and reduced groundwater buffer capacity. In addition, water resources system is also affected by non- point source pollution, resource allocation and security impact, which lead to the diversity of water resources system risk and thus threaten the health of life and non-life.

3.3 Risk Management

During the quantitative ranking phase, 13 scenarios with high risks were selected from the set of water resource system risk scenarios. Because of the characteristics of the water resource system, each high-risk scenario has at least one corresponding quantitative index for water resource system risk evaluation and management. Finally, the 33 comprehensive evaluation indices are listed in Table 9 to address the 13 high-risk scenarios. The assessment index system of water resources system risk should be established by considering specific regional backgrounds and research scales. Therefore, the assessment index system for a specific research should be established by deleting or extending index from the index system proposed in the study, on basis of the geographical location, resources, environment, humanities, etc. of the region.

4 Conclusions

In order to identify the risks contained in the water resources system in detail, this paper aims at constructing as complete and quantifiable risk index set as possible. Based on the basic characteristics of the water resources system, the HHM framework is used for comprehensive risk identification. Then through the RFRM theory, the occurrence probability of risk scenarios is calculated, ranking, and filtered. The final high-priority scenarios include hydrological factors, human factors, geological factors, non-point sources, resource allocation, life, non-life, and safety. In this paper, the causes of high-priority scenarios are analyzed from the research direction and mechanism of high-priority scenarios, which proves the effectiveness of the HHM framework and RFRM approach for identifying risks in water resources systems. Additionally, 33 quantifiable, collectable, and operable indicators are used to index high-priority scenarios and to provide indicators for accurate assessment and management of water resources system risks in the future.

Currently, the water resource system risk problem has become a critical concern around the world, and various scholars are devoted to exploring ways to avoid water resource system risk. However, a precondition of water resource system risk management is the comprehensive identification of water resource system risks so that each potential issue can be addressed. A water resource system is a large-scale system that supports human activity, and simple risk identification methods cannot provide a comprehensive view of the problem. Therefore, the HHM framework is employed to identify correlations between sub-systems. In this research, the water resource system operational process is decomposed to investigate risks between sub-

Table 9 Risk scenario indices

Major hierarchy	Risk scenario	Risk characteristics	Typical risk index
Surface water	C_2 hydrological factor	The effect of the hydrological factor on the surface water includes problems such as uneven annual runoff distribution, gradual increase in sediment concentration, and supply source conversion.	1. Proportion of monthly precipitation in annual precipitation: Reflect the risks of flood, drought, etc. 2. Sediment concentration: Reflecting the risk of river flow breakage, flood disaster, river channel shrinkage, etc. 3. Proportion of glacier melt water in total water resource: Reflecting the risks of water resources systems in the context of global warming.
	C_6 human factor	Surface water sources are classified into three categories, including river water, lake and reservoir water, and pond water. Humans alter the fundamental characteristics of these sources, there by affecting surface water safety.	1. Proportion of hydraulic project investment in total GDP: Reflect the degree of state support for water conservancy projects. 2. Proportion of water supply from the water storage project: Reflects the ability to regulate water resources in response to floods and droughts. 3. Surface water development and use: Reflecting the ability of surface water resources development, if the value is too high or too low, it means that the surface water resources have not been properly used.
Groundwater	D_2 hydrological factor	Runoff infiltration and pothole water storage are major groundwater supply sources. Hydrological factors significantly affect groundwater formation.	1. Groundwater availability:Reflect the degree of development of groundwater. 2. Groundwater aquifer thickness:Reflect the groundwater moisture content and supply capacity in different seasons.
	D_4 geological factor	Geological factors affect supply type, discharge intensity, and runoff condition and subsequently affect groundwater variation, magnitude, and rate.	1. Soil porosity:Reflects the ability of the soil to store water and supply springs and wells. 2. Soil water infiltration intensity:Reflects the ability of the soil to absorb water.
	D_6 human factor	Human activity increases new supply sources or new discharge channels, thereby altering the natural path of groundwater.	1. Groundwater overuse rate:Reflects the problem of over-exploitation of groundwater. 2. Groundwater development and use rate: Reflect the degree of groundwater utilization. 3. Groundwater exploitation modulus:Reflects the ability of groundwater exploitation.
Quantity	F_2 hydrological factor	Hydrological factors primarily manifest in the form of precipitation variation and consecutive wet or dry years, which affect the water resource quantity.	1. Runoff depth:Reflect the abundance of surface water. 2. Water generation modulus: Reflect the plentiful of surface water. 3. Proportion of surface water and groundwater in total water resource: Reflects the ability of surface water and groundwater to transform into each other.

Table 9 (continued)

Major hierarchy	Risk scenario	Risk characteristics	Typical risk index
	F_4 human factor	Human activity, extreme weather-induced ecological damage, and water resource overuse reduce water resource quantity.	1. Water resource supply-demand ratio:Reflects the ability of supply to meet demand.
Quality	G_2 non-point source	Substances such as nitrogen and phosphorus nutrients enter bodies of water increasing the suspended substance concentration and poisonous and harmful substance content and decreasing dissolved oxygen. Water bodies develop eutrophication and acidification, which directly damages the living environment of aquatic organisms and leads to an aquatic ecosystem imbalance.	1. COD and NP element concentrations: Reflect the level of water pollution. 2. Water body pH: Reflect the degree of water pollution.
Management	H_1 resource distribution	When humans allocate and use water resources during social and economic development, ecosystem health and environmental values should also be considered.	1. Industrial water reuse rate: Reflect the ability of industry to save water and reduce pollution. 2. Ratios of agriculture, industry, and residential water consumption: Reflect the rationality of regional water resources allocation. 3. Proportion of ecological water consumption: Reflects the ability to ensure the supply of ecosystem water.
	H_2 safety	Human life safety and infrastructure usage safety can only be guaranteed by satisfying production and living water safety requirements.	1. Ratio of qualified drinking water: Reflect drinking water conditions. 2. Project accident rate: Reflect the degree of safe operation of water conservancy projects.
Ecological	I_1 life	Ignoring the effect of organisms such as animals and plants on the balance of the water resource system will lead to exacerbated soil erosion and ecological imbalance.	1. Bio-extinction index: Reflect the degree of water pollution. 2. Vegetation coverage: Reflect the richness of plant resources and the degree of greening.
	I_2 non-life	Air pollution-induced water-quality deterioration and soil-pollution-induced soil erosion acceleration should be included.	1. PM2.5 concentration: Reflect the degree of air pollution. 2. Soil salinization rate: Reflect the influence of soil quality on groundwater quality.
Social	K_2 life	Escalated demand from human lifestyle and spiritual civilisation increases demands on water resource.	1. Water supply and usage modulus: Reflect the ability of the region to adjust production and domestic water consumption. 2. Water supply per capita: Reflect changes in seasonal water use in the region. 3. Water resource per capita: Reflects the extent to which the country can use water resources. 4. Urbanisation rate: Reflect the flow of population. 5. Engel coefficient: Reflect the residents' income level.

systems, which overcomes the deficiency of conventional identification methods, including the lack of a holistic approach and comprehensiveness. Over time, there will be more elusive risk sources in water resource systems, and the HHM framework should be extended to address these new requirements for risk identification. After water resource system risks are identified, RFRM theory is applied to the major risk scenarios for ranking and filtering to identify the high-risk scenarios. Water resource risk quantification via indices provides a solid theoretical foundation for future water resource risk evaluation.

Acknowledgements The authors wish to thank the reviewers and the editor for their valuable suggestions. In addition, the authors wish to thank the National Natural Science Foundation of China (grant no. 51679040); the Natural Science Foundation of Heilongjiang Province of China (General Project, grant no. E2016004) for their financial support; University Nursing Program for Young Scholars with Creative Talents in Heilongjiang Province of China (No.UNPYSCT-2017022) and Postdoctoral Scientific Research Developmental Fund of Heilongjiang Province of China (No.LBH-Q17022).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest in this work.

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