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RESEARCH ARTICLE

Risk evaluation of groundwater leakage in coal seam goaf: a case study in the Lingxin Mining Area

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Abstract

It is of great importance to determine the risk grades of the leakage and non-leakage cases of concentrated saltwater from an underground reservoir for the safe operation of reservoirs and environmental protection. In this paper, the model of risk evaluation for environmental pollution of an underground reservoir stored with concentrated saltwater is established. Moreover, the effects of different influencing factors on the risk grades are investigated, along with an uncertainty analysis. In addition, the risk grade of Lingxin Mining Area is calculated, which can contribute to the prevention and control of pollution in the future for that area. The results show that the water quality complexity of mine water is the most significant indicator for risk grade determination. The certainty of weak-risk grade for environmental pollution caused by an underground reservoir when there is no leakage is more than 60% in the Lingxin Mining Area, and the risk grade becomes a strong-risk grade rapidly after concentrated saltwater leakage is considered. This research can provide a theoretical basis for risk control and management of underground reservoirs storing concentrated saltwater.

Keywords Concentrated saltwater · Risk evaluation · Underground reservoir · Environmental pollution · Evaluation indicator

Introduction

Risk evaluation is a sustainable environmental problem mitigation approach, which involves the fields of ecology, health, water quality, and so on (You and Zhang 2018; Zhang et al. 2013; Limayem and Martin 2014; Çelebi et al. 2014; Bi and Si 2012). For different evaluation fields, the possibility and severity of risk can be quantitatively assessed by formulating corresponding evaluation criteria or systems (Barzegar et al. 2019). Taking groundwater risk evaluation as an example, Tabassum (2019) evaluated arsenic contamination and associated health risks in a previously unexplored groundwater study in Hasilpur, Pakistan, which highlights the importance of groundwater risk evaluation. Water inrush hazard is a major threat to safe mining and tunnel construction (Ma et al. 2019a). Ma (2019b) analyzed the effect of particle erosion on mining-induced water inrush hazard. Furthermore, the evaluation of the hydraulic properties' evolution of granular sandstones in relation to groundwater inrush within faults was studied (Ma et al. 2017).

The commonly used methods of risk evaluation are divided into six categories: reliability risk evaluation method (Liu et al. 2019; Wang et al. 2018), overlay and index methods (Shrestha et al. 2017; Boufekane and Saighi 2018), factor analysis method (Zhuang et al. 2018), statistical method (Jafari et al. 2016; Li et al. 2007), process mathematical simulation method (Bošnjak et al. 2012; Aydi 2018), and fuzzy mathematics method (Zuo et al. 2019). Because of its strong viability and high practicability, the overlay and index methods approach has become the most widely used groundwater risk evaluation method (Rezaei et al. 2015).

The research pertaining to groundwater pollution risk evaluation is generally more focused on solute transport, sewage leakage, and so on. In view of the shortage of water in some mining areas and the low utilization rate of mine water, Chinese scholars innovatively put forward the method of

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constructing coal mine underground reservoirs (Gu 2014; Gu et al. 2016; Cao et al. 2016). Generally speaking, an artificial dam is constructed after the coal seam mining is over, which connects the discontinuous pillar dam to form a water storage space. The mine water is then discharged to this underground reservoir. It is purified through the filtering, adsorbing, and precipitating of gangue in the coal seam goaf to realize the secondary utilization of mine water and effectively protect groundwater resources (Gu 2015). However, mine water purification will produce a large volume of concentrated saltwater, which is considered as high-salinity sewage (Lazareva et al. 2019; Ashraf et al. 2019). In practical engineering, this high-salinity sewage is sealed long-term in an underground reservoir (Jiang et al. 2018). In reality, the environmental risks and key technologies of concentrated saltwater storage should be fully studied to avoid the secondary pollution of groundwater systems caused by the leakage of concentrated saltwater from the underground reservoirs. It is of extreme importance to determine the environmental pollution risk level of concentrated saltwater storage and its impact on human health when doing a water resources assessment, however, which has not been studied so far. Therefore, the establishment of a reasonable risk evaluation indicator system for environmental pollution caused by concentrated saltwater storage will help to improve the control and the management of such risks.

In this paper, four research aspects are used in combination to generate a practical engineering approach when considering underground reservoirs used for concentrated saltwater storage. First, the indicator system of pollution risk evaluation for underground reservoir with concentrated saltwater is established by the overlay and index methods. Second, taking Lingxin Mining Area as an example, the risk grade of environmental pollution of the underground reservoir stored with concentrated saltwater is determined. Third, according to the Monte Carlo simulation, uncertain factors affecting the environmental pollution risk grade are discussed. Fourth and finally, the risk grades of pollution caused by an underground reservoir before and after the leakage of concentrated saltwater are determined for the control and management of the risks. The results of this study will fill in the blanks for environmental pollution risk evaluation of underground reservoirs stored with concentrated saltwater and will provide a theoretical fundamental for safe underground reservoir construction.

Study area

The Lingxin Mining Area is located 50 km east of Lingwu City, Ningxia Hui Autonomous Region, China (Lai et al. 2006), as shown in Fig. 1. The climate of the area is a mid-temperate, semi-arid, continental monsoon climate. The annual maximum rainfall is 299.1 mm, and the annual evaporation is 2771 mm. The overall mining area is divided into six smaller mining areas. At present, the first, second, and third mining areas have finished production, the fourth and fifth mining areas are in production, while the sixth mining area has not yet been in production. The output of raw coal is 3.2 million tons per year, and the total amount of mine water is about 3.94 million m^3/year. The salinity of the mine water is 5000 mg/L, which is a typical high-salinity level. The storage site of concentrated saltwater is selected in the north wing of the first mining area (Jiang et al. 2018).

The demonstration engineering project about concentrated saltwater storage in Lingxin Mining Area was entirely built by Shenhua Ningxia coal industry group limited company, and it has become a typical application for underground storage of concentrated saltwater.

Materials and methods

Parameter analysis of mining area

According to the field investigation results of technicians in Lingxin Mining Area, it is possible to predict the likelihood of groundwater environmental pollution caused by concentrated saltwater storage. Based on the geological and production data of the mining area, the relevant parameters for calculating the environmental pollution risk grade of the underground reservoir stored with concentrated saltwater are obtained, as shown in Table 1.

Model of risk evaluation

Risk analysis

The overlay and index methods are used to establish a groundwater pollution risk evaluation system, including risk analysis, indicator screening, and weight calculation. Considering the practical engineering background of underground reservoirs of concentrated saltwater storage, there are three kinds of risks that can be predicted: (1) the collapse of the overlying strata of the underground reservoir, (2) the leakage of concentrated saltwater from the underground reservoir, and (3) some safety accidents caused by human activities, such as a gas explosion. Based on the object of the study and the possibility of risk occurrence in the underground reservoir in this paper, the second risk is taken as the basis for determining the evaluation system, and related elaborations are made.

Considering the possible mode and process of environmental pollution by an underground reservoir stored with concentrated saltwater, and considering the actual situation of long-term underground storage of concentrated saltwater, the pollution risk can entirely be roughly summarized as a "source," "channel," and "receptor" type, which we define as the criterion layer. "Source" refers to the pollution source, that is, the underground reservoir with concentrated saltwater storage.

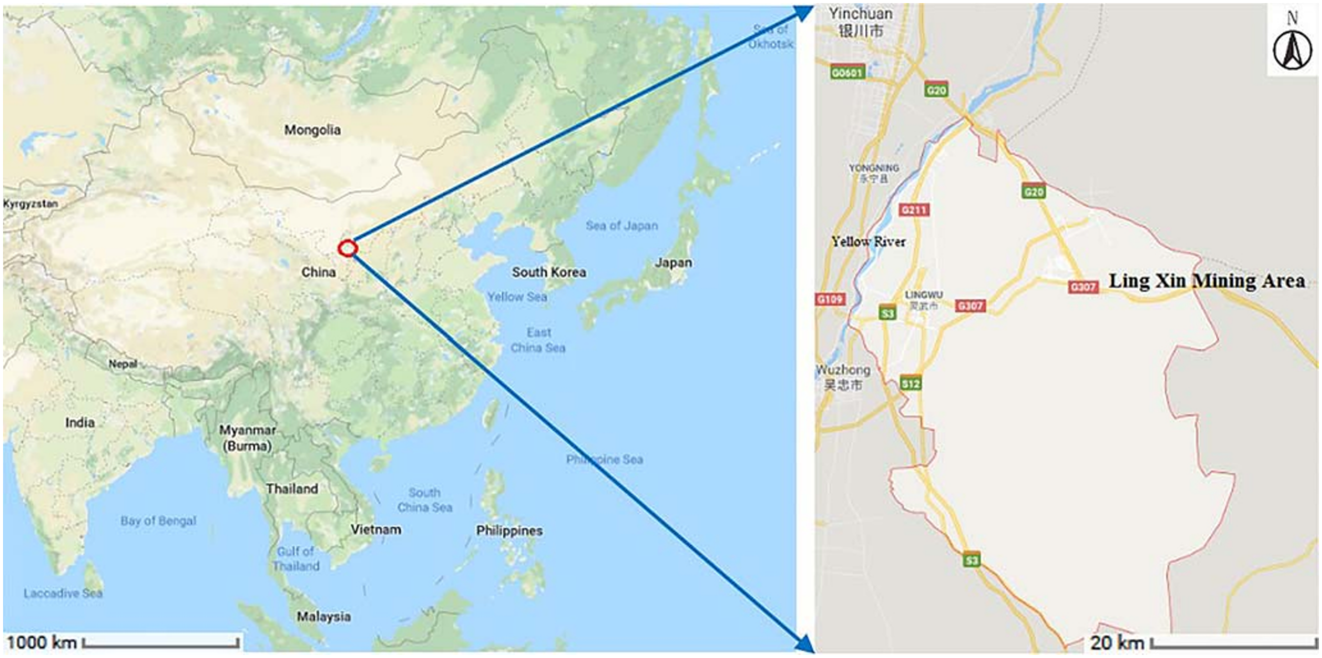


Fig. 1 Location of Lingxin Mining Area

"Channel" refers to the pollution channel, that is, the migration channel of the leaked concentrated saltwater from the reservoir to polluting groundwater and causing the underground pollution. "Receptor" refers to the pollution receptor, that is, the groundwater environment polluted by the concentrated saltwater.

The underground reservoir stored with concentrated saltwater is regarded as a pollution source because the concentrated saltwater containing certain pollutants may flow out of the reservoir. There are many possible points where the potential leakage may happen, such as the outflow at the junction of the coal pillar dam or the artificial dam. In this situation, the

Table 1 Relevant data of environmental pollution risk grade calculation of underground reservoir stored with concentrated saltwater in Lingxin Mining Area

Related parameters	Values	Data sources
Mining area	27.4937 km^2	Field data
Influencing radius of mine drainage	0.3 km	Empirical value
Normal water inflow in mine	430 m^3 h^{-1}	Jiang et al. 2018
Water quality complexity of mine water	Complex	Field data
Concentration of chloride ion in concentrated saltwater	5000 mg/L	Field data
Permeability coefficient of dam bedrock	0.67 m/day	Field data
Aquifer thickness	21.74 m	Field data
Porosity of dam bedrock	0.18	Empirical value
Fault water transmissibility	Weak	Wu 2011
Specific location of receptor aquifer	Downstream	Field data
Diffusion coefficient of concentrated saltwater	1×10^{-6} m^2/s	Empirical value +Field data
Height of caving zone	24 m	Xiang et al. 2017+ Empirical value
Rock bulking coefficient	1.35	Zhang and Xu 2018+Empirical value
Groundwater intake quantity	8000 m^3	Empirical value + Field data
Concentration of chloride ion in polluted receptor	48 g/L	Empirical value +Field data
Chemical oxygen demand	33.11 mg/L	Field data
Ammonia nitrogen concentration	0.91 mg/L	Empirical value +Field data
Types of organic solvent	Petroleum	Field data

pollutants enter the underground aquifer through infiltration, dilution, and contamination at a certain speed.

Indicator screening

In order to select each risk evaluation indicator more reasonably, scientifically, and effectively, before screening the indicator, some factors related to underground reservoirs that do not affect the risk grade, such as the density of coal and rock mass, can be excluded by consulting relevant experts. This ensures the efficiency and rationality of the selected evaluation indicators. According to the pollution risk guiding ideology of "source," "channel," and "acceptor," the 3 first-level indicators and 21 second-level indicators can be retained. The specific results are shown in Table 2. The 21 second-level indicators are collectively called as the indicator layer. Among them, it is not straightforward to determine the risk evaluation indicators of the pollution receptor, namely pollution area, frontier concentration of pollution receptor, and average concentration of pollution range in mining area. Therefore, it is necessary to include the relevant COMSOL simulation results as the data of these 3 indicators.

Weight calculation

According to the principle and content of analytic hierarchy process (Kheybari et al. 2019; Barzegar et al. 2019; Xu 1988; Nagai 2014), determining the weight of environmental pollution risk evaluation indicators for underground reservoirs stored with concentrated saltwater is divided into five steps: (1) establishing the hierarchical structure model, (2) constructing the judgment matrix, (3) computing the maximum characteristic root of each judgment matrix and its corresponding eigenvector, (4) hierarchical single sorting and testing of its consistency, and (5) hierarchical total sorting computation.

Table 3 Standard value of mean random consistency indicator

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

By consulting and consolidating the opinions of 14 hydrogeologists and 7 environmental protection experts from China Energy Investment Corporation Limited, China Environmental Protection Center, Lingxin Mining Area, and University of Science and Technology Beijing, the corresponding results are quantified, and then, the judgment matrix is constructed. Hierarchical single sorting is utilized to determine whether the constructed judgment matrix can pass the consistency test. The test coefficient is defined as follows:

$$CR = \left(\frac{\lambda_{\max} - n}{n - 1}\right) / RI \tag{1}$$

where CR is the test coefficient, $\lambda_{\max}$ is the maximum characteristic root corresponding to the judgment matrix, and n is the order of the judgment matrix. RI is a random consistency indicator, which is related to the order of the judgment matrix as shown in Table 3. For a consistent matrix, CR should be less than or equal to 0.1 (Neshat and Pradhan 2015; Yang et al. 2017).

Evaluation system

Based on the relevant research contents of risk analysis, indicator screening and weight calculation, and summarizing all the data, the risk evaluation indicator system of environmental pollution of an underground reservoir stored with concentrated saltwater can be determined, as shown in Table 4. It should be pointed out that the values for pollution area, the frontier

Table 2 Environmental pollution risk evaluation indicators for an underground reservoir stored with concentrated saltwater

	The first-level indicators (the criterion layer)	The second-level indicators (the indicator layer)
Risk evaluation indicator system of environmental pollution of underground reservoir stored with concentrated saltwater (the target layer)	Pollution source risk identification	Mining area, influencing radius of mine drainage, normal water inflow in mine, water quality complexity of mine water, concentration of chloride ion in concentrated saltwater
	Pollution channel risk identification	Permeability coefficient of dam bedrock, aquifer thickness, porosity of dam bedrock, fault water transmissibility, specific location of receptor aquifer, diffusion coefficient of concentrated saltwater, height of caving zone, rock bulking coefficient
	Pollution receptor risk identification	Groundwater intake quantity, concentration of chloride ion in polluted receptor, chemical oxygen demand, ammonia nitrogen concentration, types of organic solvent, pollution area, frontier concentration of pollution receptor, average concentration of pollution range

Table 4 Risk evaluation indicator system of environmental pollution of an underground reservoir stored with concentrated saltwater

Serial number	Indicators (unit)	Basis of data	High-risk grade		Middle-risk grade		Low-risk grade	
1	Mine mining area (km^2)	Statistical Information	≧ 100		30~100		≦ 30	
2	Influencing radius of mine drainage (km)	Technical Guidelines for environmental impact evaluation (HJ 610–2011)	≧ 1.5		0.5~1.5		≦ 0.5	
3	Normal water inflow in mine ($m^3\ h^{-1}$)	Regulations on water control in coal mines	≧ 600 (Northwest China ≧ 180)		180~600 (Northwest China 90~180)		≦ 180 (Northwest China ≦ 90)	
4	Water quality complexity of mine water	Technical guidelines for environmental impact evaluation (HJ 610–2011)	Number of pollutant types ≧ 2 Water quality indicators to be predicted ≧ 6		Number of pollutant types ≧ 2 Water quality indicators to be predicted < 6	Number of pollutant types = 1 Water quality indicators to be predicted ≧ 6	Number of pollutant types = 1 Water quality indicators to be predicted < 6	
5	Concentration of chloride ion in concentrated saltwater (g/L)	Environmental criteria for modern coal chemical construction projects	≧ 80		50~80		≦ 50	
6	Permeability coefficient of dam bedrock (m/day)	Empirical value of technical personnel in mining area	≧ 50		10~50		≦ 10	
7	Aquifer thickness (m)	Expert consultation	≧ 60		30~60		≦ 30	
8	Porosity of dam bedrock (%)	Expert opinions and statistics information	≧ 35	20~35	10~20		≦ 10	
9	Fault water transmissibility	Geological data	Strong		Middling		Weak	
10	Specific location of receptor aquifer	Life experience	Downstream	Lateral downstream	Midstream		Upstream	
11	Diffusion coefficient of concentrated saltwater ($10^{-9}\ m^2/s$)	References	≧ 6		3~6		≦ 3	
12	Height of caving zone (m)	Regulations for coal pillar setting and coal mining under pressure in buildings, water bodies, railways, and main roadways	≧ 30	20~30	10~20		≦ 10	
13	Rock bulking coefficient	References	≧ 2.5	1.5~2.5	1.0~1.5		≦ 1.0	
14	Groundwater intake quantity (m^3)	Technical guideline for delineating source water protection areas (HJ T338-2007)	≧ 500,000		10,000~50,000		≦ 10,000	
15	Concentration of chloride ion in polluted receptor (g/L)	Environmental criteria for modern coal chemical construction projects	≧ 80		50~80		≦ 50	
16	Chemical oxygen demand (mg/L)	Water quality determination of chemical oxygen demand—dichromate method	≧ 40	30~40	20~30		10~20	≦ 10
17	Ammonia nitrogen concentration (mg/L)	Quality standard for ground water (GB/T 14848—2017)	≧ 4		1~4		≦ 1	

Table 4 (continued)

Serial number	Indicators (unit)	Basis of data	High-risk grade	Middle-risk grade	Low-risk grade
18	Types of organic solvent	Expert opinions	Hydrocarbons, ketones, lipids	Ethers	Alcohols
19	Pollution area (km^2)	Simulation results	≥ 800	400~800	≤ 400
20	Frontier concentration of pollution receptor (g/L)	Simulation results	≥ 0.15	0.05~0.15	≤ 0.05
21	Average concentration of pollution range (g/L)	Simulation results	≥ 0.06	0.01~0.06	≤ 0.01

Table 5 The results of weight calculations for each indicator

Indicators	Weight
Mining area (W11)	0.0725
Influencing radius of mine drainage (W12)	0.0781
Normal water inflow in mine (W13)	0.0651
Water quality complexity of mine water (W14)	0.1399
Concentration of chloride ion in concentrated saltwater (W15)	0.1271
Permeability coefficient of dam bedrock (W21)	0.0312
Aquifer thickness (W22)	0.0340
Porosity of dam bedrock (W23)	0.0364
Fault water transmissibility (W24)	0.0212
Specific location of receptor aquifer (W25)	0.0415
Diffusion coefficient of concentrated saltwater (W26)	0.0421
Height of caving zone (W27)	0.0167
Rock bulking coefficient (W28)	0.0166
Groundwater intake quantity (W31)	0.0432
Concentration of chloride ion in polluted receptor (W32)	0.0446
Chemical oxygen demand (W33)	0.0289
Ammonia nitrogen concentration (W34)	0.0218
Types of organic solvent (W35)	0.0209
Pollution area (W36)	0.0367
Frontier concentration of pollution receptor (W37)	0.0382
Average concentration of pollution range (W38)	0.0433

concentration of pollution receptor, and the average concentration of pollution range are obtained from the COMSOL simulation results in the mining area, after simulating the leakage of concentrated saltwater from the reservoir.

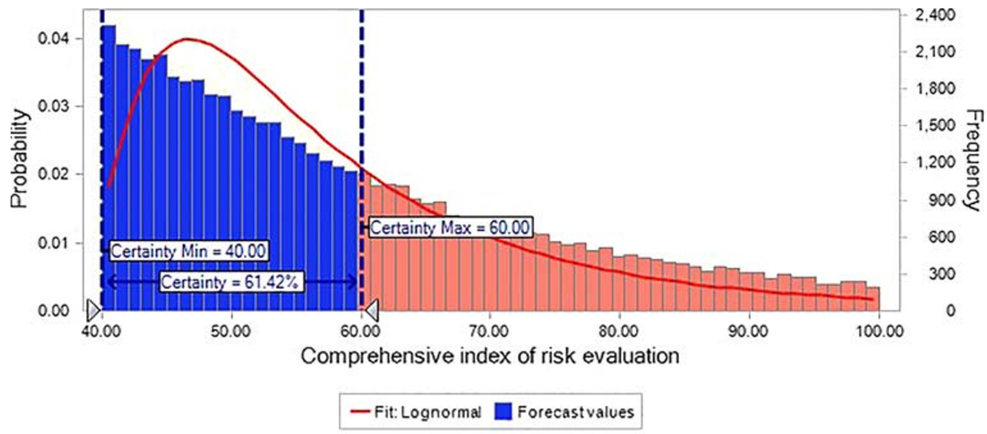
In order to quantify the risk grade, a comprehensive index model for environmental pollution risk evaluation of an underground reservoir stored with concentrated saltwater is constructed, as shown in Formula (2):

$$\beta = \sum_{i=1}^{5} \alpha_i \phi_i + \sum_{j=1}^{8} \eta_j \varphi_j + \sum_{k=1}^{5} \delta_k \gamma_k \tag{2}$$

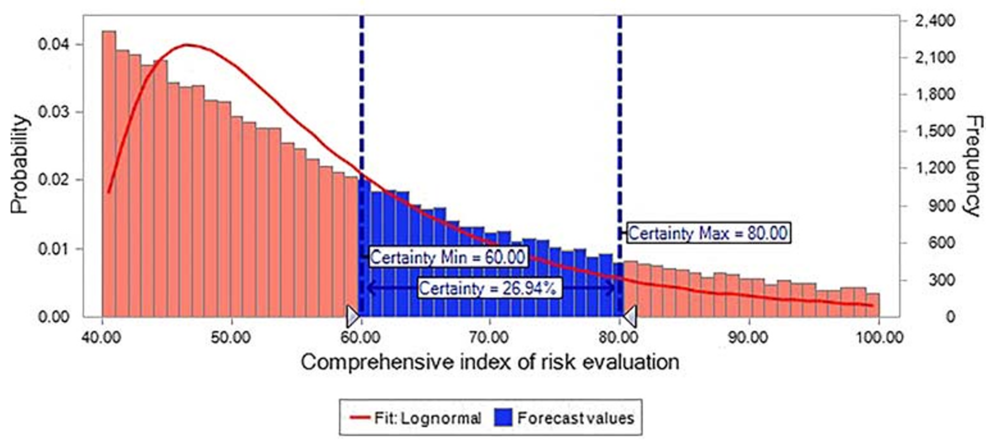
where β is a comprehensive index for environmental pollution risk evaluation of an underground reservoir stored with concentrated saltwater, α_i is the scoring value of the i_{th} pollution source risk indicator, and ϕ_i is the weight of the i_{th} pollution source risk indicator. η_j is the scoring value of the j_{th} pollution channel risk indicator, and φ_j is the weight of the j_{th} pollution channel risk indicator. δ_k is the scoring value of the k_{th} pollution receptor risk indicator, and γ_k is the weight of the k_{th} pollution receptor risk indicator.

The scoring value and weight of each risk evaluation indicator need to be determined according to the environmental pollution risk evaluation indicator system of an underground reservoir stored with concentrated saltwater. If a risk evaluation indicator belongs to the high-risk grade, its scoring value is 100 points. For the middle-risk grade and low-risk grade, the corresponding scoring values are 70 and 40 points, respectively. Through specific calculations, the comprehensive index for environmental pollution risk evaluation of an underground reservoir stored with concentrated saltwater is randomly distributed between 40 and 100. The risk grade can be divided into three categories: strong ($80 \leqq \beta < 100$), medium ($60 \leqq \beta < 80$), and weak ($40 \leqq \beta < 60$). It should be noted that considering the complexity of risk classification on an engineering site, the higher-risk grade has been included in the scope of high-risk grade, and the lower-risk grade has been

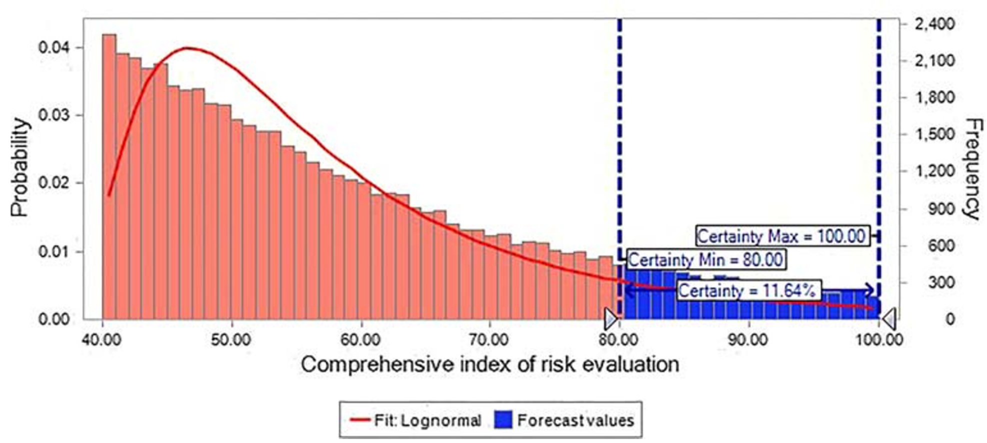
Fig. 2 Prediction diagram of comprehensive index of risk evaluation based on Monte Carlo simulation. **a** Schematic diagram of weak-risk grade prediction. **b** Schematic diagram of medium-risk grade prediction. **c** Schematic diagram of strong-risk grade prediction



(a) Schematic diagram of weak-risk grade prediction



(b) Schematic diagram of medium-risk grade prediction



(c) Schematic diagram of strong-risk grade prediction

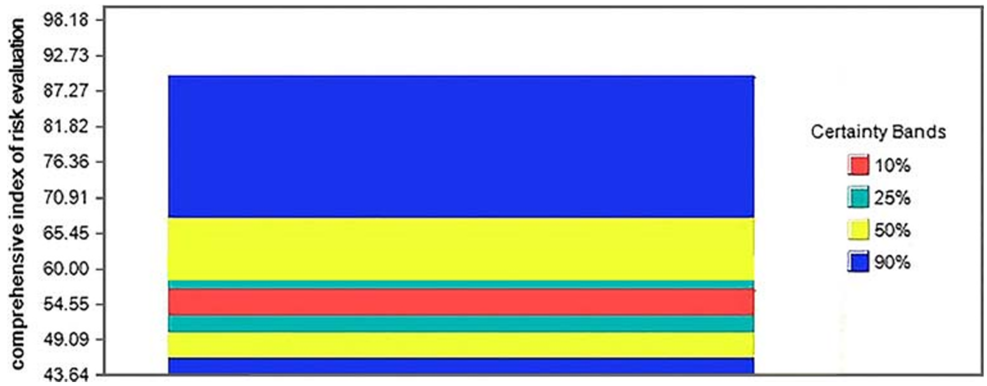


Fig. 3 Trend diagram of comprehensive index of risk evaluation based on Monte Carlo simulation

included in the scope of low-risk grade, which is convenient for an engineering site calculation.

Uncertainty analysis

It is necessary to conduct an uncertainty analysis on the factors that may lead to the occurrence of risks, which will help to strengthen the control and management of the risks. The Monte Carlo simulation method is widely used in uncertainty analysis (Qin et al. 2013; Limayem and Martin 2014; Da Silva and De Castro, 2019). This method can also be applied to the study of environmental pollution risk evaluation indicators of an underground reservoir stored with concentrated saltwater. Assuming that the data of the comprehensive index can be expressed as a probability density distribution function, the data of 21 risk evaluation indicators follow a lognormal distribution. The simulation is run 100,000 times, and the new values in the range of average ± standard deviation are randomly selected as the data.

Table 6 Simulated calculation results of evaluation indicators

Assumptions	Contribution	Rank correlation
W11	0.038977334	0.07577765
W12	0.032748446	0.06945931
W13	0.071906506	0.1029246
W14	0.612411882	0.30037023
W15	0.159876921	0.15347158
W21	0.007809851	0.03392005
W22	0.005613126	0.0287566
W23	0.008424542	0.03522964
W24	0.002437757	0.01895092
W25	0.011307717	0.04081526
W26	0.012300446	0.0425692
W27	0.001403159	0.01437767
W28	0.001987119	0.01710988
W31	0.009764574	0.03792816
W32	0.011564874	0.04127675
W33	0.007612798	0.03348939
W34	0.002969850	0.02091714
W35	0.008830960	0.01140615

Results and discussion

Consistency test of AHP

The test coefficients of the judgment matrices are calculated as 0.018707, 0.016451, 0.067457, and 0.072482. All four of the test coefficients are less than 0.1. It is therefore determined that the judgment matrices between target layer and criterion layer, and between criterion layer and indicator layer constructed in this paper pass the consistency test, which further confirms the scientific validity and rationale of the selected 21 risk indicators. Furthermore, according to the normalized processing results of each eigenvector, the corresponding weight calculations of each risk evaluation indicator is obtained and shown in Table 5. Evaluation indicators with weights greater than 10% are water quality complexity of mine water (W14) and concentration of chloride ion in concentrated saltwater (W15), while the lowest weight is that of the rock bulking coefficient (W28). The average value of the weights is 0.0476.

Risk level of concentrated saltwater without leakage

The current risk grade of the mining area can be determined by combining the parameters of the underground reservoir in Lingxin Mining Area and the risk evaluation indicator system of environmental pollution of an underground reservoir stored with concentrated saltwater in this paper. The data shows that concentrated saltwater has not leaked from the reservoir. It is therefore necessary, when determining the risk grade, to exclude the risk evaluation indicators of the pollution receptor, which are the pollution area, the frontier concentration of pollution receptor, and the average concentration of pollution

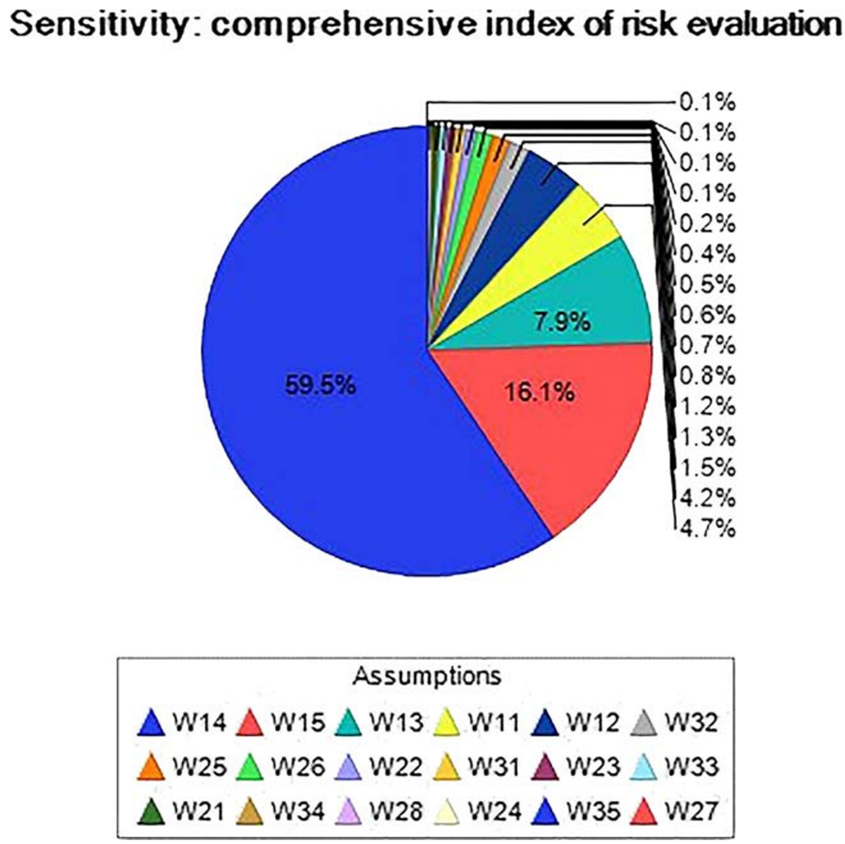


Fig. 4 Sensitivity schematic diagram of evaluation indicators

range. After detailed calculation, the value of the comprehensive index of risk evaluation can be obtained as $\beta = 58.168$.

According to the risk grade classification of environmental pollution caused by an underground reservoir stored with concentrated saltwater, the environmental pollution risk grade in Lingxin Mining Area is weak-risk grade. To elaborate, even though concentrated saltwater has not leaked from the reservoir, there are potential environmental pollution risks in the engineering treatment methods of concentrated saltwater storage. It is necessary to cooperate with environmental protection departments and issue relevant policy provisions as soon as possible.

Since concentrated saltwater has not leaked from the reservoir, Monte Carlo simulation is also carried out for the comprehensive index of risk evaluation, and the results are shown in Fig. 2. The certainty of the comprehensive index between 40 and 60 is 61.42%, which corresponds to the probability of occurrence of weak-risk grade. The certainty of the comprehensive index between 60 and 80 is 26.94%, which corresponds to the probability of occurrence of medium-risk grade. The certainty of the comprehensive index between 80 and 100 is 11.64%, which corresponds to the probability of occurrence of strong-risk grade. As observed, the probability of occurrence of weak-risk grade is higher, while that of occurrence of strong-risk grade is lower. This will help to further determine the probability of occurrence of risk grades at all levels.

Figure 3 shows that the probability of comprehensive index greater than 60 is more than 50%, corresponding to medium-risk and strong-risk grades. This will help to further predict the risk grade. Combined with the certainty of risk grade occurrence at all levels, it can be predicted that the probability of occurrence of medium-risk and strong-risk grades of the underground reservoir in Lingxin Mining Area with concentrated saltwater storage is relatively high. Therefore, it is necessary to protect the groundwater environment to the greatest extent and reduce pollution problems caused by human disturbance activities. Controlling the risk grade of Lingxin Mining Area at the weak-risk or reducing risk grade is very urgent.

According to the actual engineering experience of the mining area, an evaluation indicator with contribution between 15 and 20% is defined as having a prominent impact on the comprehensive index. An evaluation index with contribution between 5 and 15% is defined as having a moderate impact on the comprehensive index, while an evaluation index with contribution below 5% is defined as having a poor impact on the comprehensive index. The contribution calculation results are shown in Table 6. It can be found that the evaluation indicators with greater contribution are water quality complexity of mine water (W14) and concentration of chloride ion in concentrated saltwater (W15). Most of the evaluation indicators have a poor impact on the comprehensive index, such as mining area

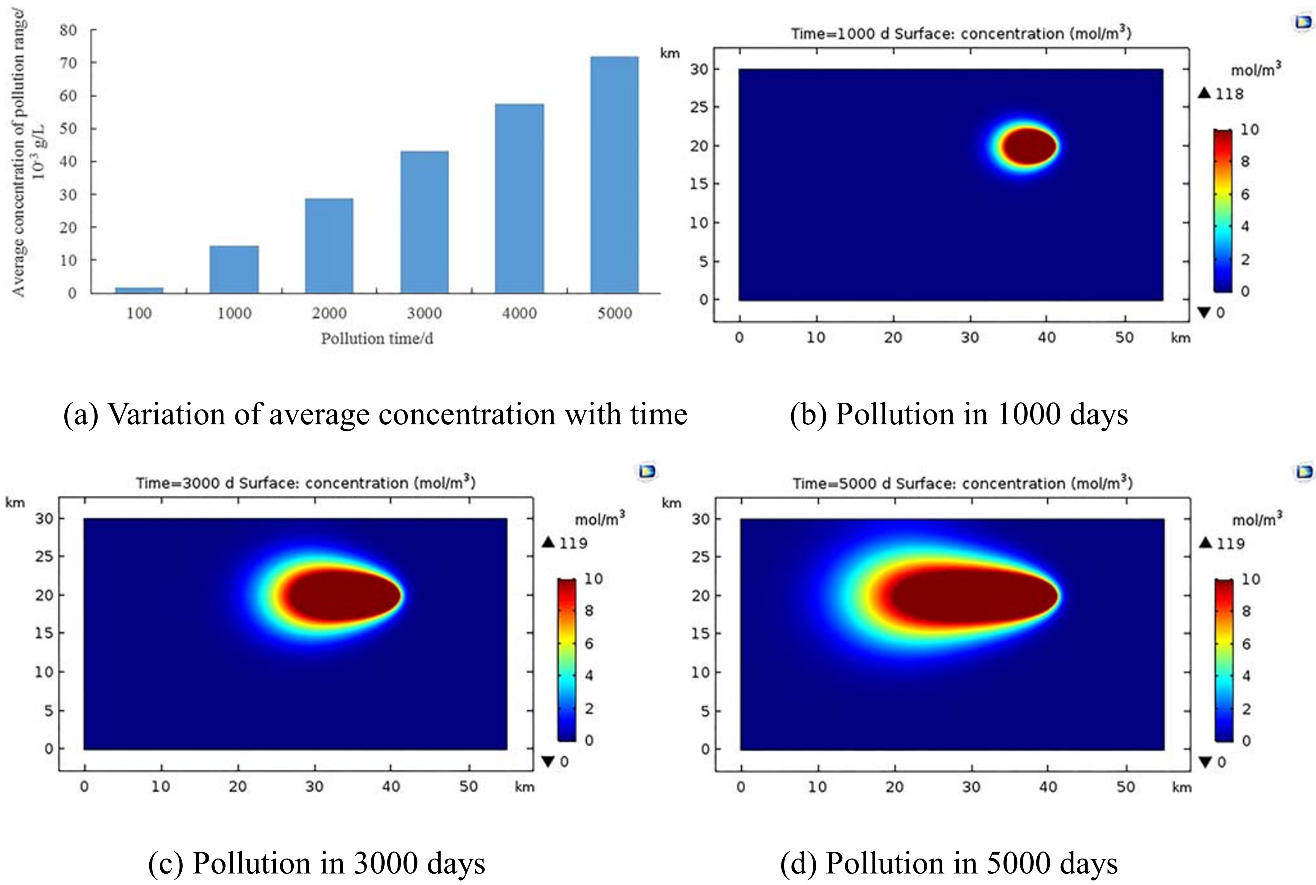


Fig. 5 Schematic diagram of pollutant diffusion in concentrated saltwater storage. **a** Variation of average concentration with time. **b** Pollution in 1000 days. **c** Pollution in 3000 days. **d** Pollution in 5000 days

(W11), permeability coefficient of dam bedrock (W21), groundwater intake quantity (W31), and so on. The normal water inflow in mine (W13) has a moderate impact on the comprehensive index; however, the impact of all evaluation

Table 7 Simulation results of pollution receptor risk evaluation indicator for the underground reservoir stored with concentrated saltwater in Lingxin Mining Area

Related parameters (unit)	Pollution time	Values	Data sources
Pollution area (km^2)	100 days	205.00064	Simulation results
	1000 days	354.69982	
	2000 days	475.72924	
	3000 days	685.63608	
	4000 days	837.71450	
	5000 days	1002.03392	
Frontier concentration of pollution receptor (g/L)	100 days	185.78215×10^{-3}	Simulation results
	1000 days	109.61335×10^{-3}	
	2000 days	107.57210×10^{-3}	
	3000 days	98.32435×10^{-3}	
	4000 days	89.27895×10^{-3}	
	5000 days	67.24765×10^{-3}	
Average concentration of pollution range (g/L)	100 days	1.43587×10^{-3}	Simulation results
	1000 days	14.35940×10^{-3}	
	2000 days	28.71986×10^{-3}	
	3000 days	43.07925×10^{-3}	
	4000 days	57.43900×10^{-3}	
	5000 days	71.78810×10^{-3}	

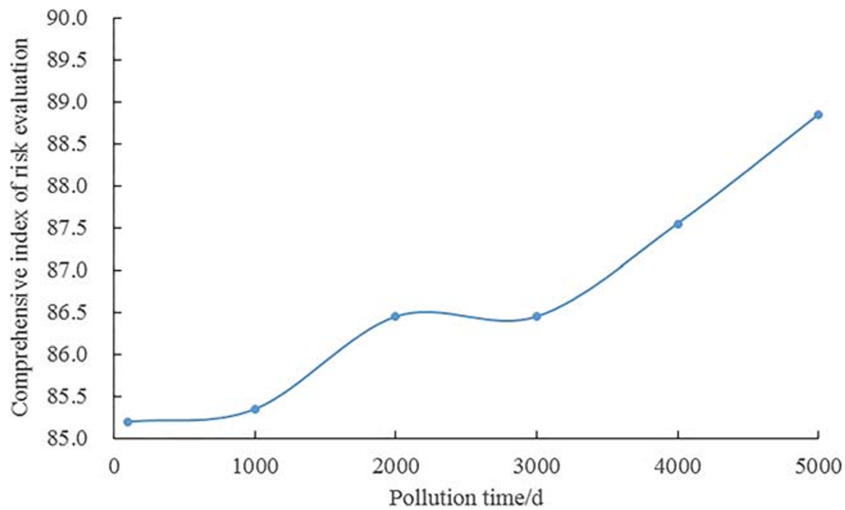


Fig. 6 Comprehensive index of risk evaluation for concentrated saltwater storage

indicators on the comprehensive index is positively correlated. Considering that most of the water in the underground reservoir stored with concentrated saltwater is mine water, the more complex the water quality of mine water is, the higher the risk is, and the greater the contribution to the comprehensive index is. Therefore, in order to reduce the environmental risk of the concentrated saltwater, the mine water with water quality of less complexity should be stored as far away as possible.

The sensitivity analysis results of the Monte Carlo simulation are shown in Fig. 4. The evaluation indicators sensitive to the comprehensive index are the water quality complexity of mine water (W14), the concentration of chloride ion in concentrated saltwater (W15), and the normal water inflow in mine (W13). The corresponding sensitivity values are 59.5%, 16.1%, and 7.9%, respectively. The sensitivity values of all other evaluation indicators are individually below 5%. When a sensitivity value is higher, an evaluation indicator is more sensitive in how it affects the comprehensive index, and in turn how it affects the classification of the risk grade.

Risk level of concentrated saltwater with leakage

In this section, the environmental pollution caused by an underground reservoir stored by concentrated saltwater is simulated by using relevant engineering data provided by technicians from Lingxin Mining Area and combining it with the actual size and physical parameters of the mining area. The environmental pollution risk grade of concentrated saltwater leaking from the reservoir is thus obtained. According to the simulation results of Fig. 5, it can be seen that the pollution area of pollutants in 1000 days, 3000 days, and 5000 days is getting consistently larger with time, which results in the rapid increase of average concentration of pollution range. Detailed data is shown in Table 7.

According to the risk evaluation indicator system and comprehensive index model of environmental pollution of an underground reservoir stored with concentrated saltwater established in this paper, combined with the relevant data in Tables 1 and 7, the comprehensive risk evaluation index of concentrated saltwater leakage can be obtained as shown in Fig. 6. It can be seen that the comprehensive index of environmental pollution risk evaluation caused by the leak of concentrated saltwater increases gradually as pollution time increases, and it is in the strong-risk grade. Consequently, we consider that the results predicted by the Monte Carlo simulation are verified. Therefore, it is necessary to tighten the management of the underground reservoir stored with concentrated saltwater and formulate reasonable prevention and control measures.

Conclusions

This paper studies the risk levels of leakage and non-leakage of concentrated saltwater of an underground reservoir of the Lingxin Mining Area, which is of great significance to environmental protection. Specifically, the model of risk evaluation for environmental pollution of an underground reservoir stored with concentrated saltwater is established by the overlay and index methods. It can facilitate the quantitative risk evaluation of groundwater leakage.

Through an uncertainty analysis of the influencing factors of the risk grade, when there is no leakage of concentrated saltwater, it can be found that water quality complexity of mine water is the most significant factor with the weight value of 14%. Furthermore, as determined by the Monte Carlo simulation, the contribution and sensitivity of water quality complexity of mine water to risk grade classification are 61.24% and 59.5%, respectively. Above all, the certainties of the weak-risk grade, the medium-risk grade, and the strong-risk grade for the environmental pollution caused by an underground reservoir with concentrated saltwater storage in Lingxin Mining Area are 61.42%, 26.94%, and 11.64%, respectively. However, when it is considered that there is concentrated saltwater leakage, the environmental pollution risk grade increases greatly as compared to a non-leakage situation, and it falls within the strong-risk grade. Therefore, the engineering treatment method of long-term concentrated saltwater sealing needs to be implemented in accordance with the environmental protection requirements of each mining area.

This research can act as a reference and guide for risk control and management of underground reservoirs stored with concentrated saltwater and can have a very broad application prospect.

Author contributions Hongqing Song designed the entire project and paper. Jianjian Xu and Lianzhi Yang established the model and analyzed the results. Jie Fang and Zhiguo Cao were in charge of underground reservoir construction and provided the real field data. Tianxin Li contributed to the paper writing.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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