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Risk assessment on the CCUS project using risk breakdown structure methodology: A case study on Jilin oilfield CO_2-EOR Hei-79 block

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Abstract: The risk potential matrix method can be used as a reference for the optimization of the traditional risk matrix in geological CO_2 storage. This study used monitoring data for environmentally sensitive receptors in the Jilin Oilfield CO_2-enhanced oil recovery (CO_2-EOR) Hei-79 block in conjunction with a hazard event store to create an updated risk assessment of CO_2 capture, use, and storage (CCUS) as a guide for risk management. The assessment built upon the overall project operation status to evaluate six and five sub-categories of hazard and sensitivity, respectively. The environmental sensitivity threshold integrated ecosystems and secondary geological disasters to amplify potential risks. The results of the risk assessment of the CO_2-EOR Hei-79 block in the Jilin Oilfield showed that despite an overall risk level of II, the hazard level resulted in an unacceptable increase in overall risk. Formations are usually stimulated by fracturing in Jilin Oilfield, particularly for oil and gas production. © 2021 Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: risk assessment; risk potential matrix; CCUS; CO_2-EOR; hazard and sensitive

Introduction

Increases in global greenhouse gas emissions have had seriously impacts on society and ecosystems. Many countries have adopted carbon capture, use, and storage (CCUS) as an essential measure to achieve zero CO_2 emissions.[1–2] The permanent underground storage of high-pressure supercritical CO_2 can be associated with risks of affecting the surrounding environment, particularly when storage displaces other natural resources such as oil and natural gas.[3] Therefore, the premise of permanent CO_2 storage requires a complete risk assessment.

Most risk assessment systems focus on the path of CO_2 leakage and provide a quantitative approach to simulating the risk of leakage from storage sites based on simulations of geophysical fluid flow, three-dimensional geospatial data, and carbon dioxide (CO_2) plume range.[4–9] These methods track the CO_2 plume from a single perspective and assess the possible risks. The risk matrix method evaluates risk from different perspectives. This method considers both the

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possibility of dangerous accidents and the impact of the surrounding environment through the classification of possibility and severity. Consequently, the risk matrix method has been adopted as the standard method for assessing risk of CCUS in China.[10–12] Under the risk matrix method, the possibility and severity of a project are evaluated by expert scoring. However, there are several disadvantages associated with the application of the risk matrix method to CCUS. The risk matrix method pays insufficient attention to site characteristics, operation technology, operation management, and other aspects before and after injection. Moreover, an emphasis on qualitative evaluation within the method results in insufficient focus on the actual operation state.[13]

Therefore, the current study attempted to optimize the application of the risk matrix method to CCUS. The risks of any construction project include the hazards associated with the project and the degree of impact of environmental receptors. Risk quantification of CCUS by the risk matrix method can be achieved by including hazard and degree of impact as parameters. Multi-angle project investigation and environmental monitoring data were used to establish a risk potential matrix to refine risk factors and accurately assess risks. The risk potential is defined as:

$$\text{Risk Potential (RP)} = P(\text{Potential of hazard}) \times D(\text{Degree of sensitivity}) \quad (1)$$

The risk potential matrix divides risk into hazard and sensitivity. Hazard represents the types of project storage and the possibility of potential hazards associated with the process facilities. Sensitivity refers to the degree of influence of interference on environmental receptors. The risk breakdown structure (RBS) method is used to further divide risk and sensitivity. The hazard is divided into six sub-categories: (1) infrastructure; (2) site characteristics; (3) technical operation; (4) natural factors; (5) human activities and; (6) social external factors. Sensitivity is subdivided into five sub-categories: (1) atmosphere; (2) surface water; (3) groundwater; (4) soil microorganisms and; (6) reservoir. Each category will also be specifically divided into evaluation indicators. The hazard assessment considers different storage types and storage scales and the environmental receptor threshold provides a reference for sensitivity assessment.

The current study used the risk potential matrix method to evaluate the risk of a CO_2 storage project in the Jilin Oilfield Hei-79 block. The storage conditions of the site were fully investigated and the environmentally sensitive targets were monitored for 10 days. The level of risk was divided according to the characteristics of the project and the site conditions and the traditional risk matrix method was optimized for the risk assessment.

Project and method

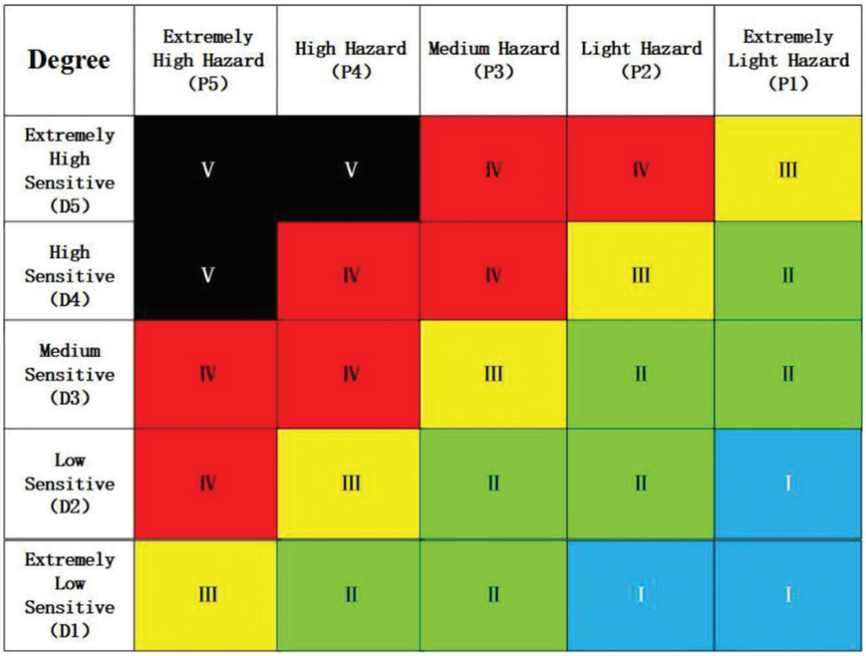
Brief introduction of the Hei-79 block

The Jilin Oilfield CO_2-enhanced oil recovery (CO_2-EOR) project focused on studying the injection and underground storage of CO_2 in Songyuan, China. As of 2020, over 145 Mt CO_2 has been stored at a depth of 2.3 km. Total oil production in the project increased by 130,000 tons, resulting in the Jilin Oilfield CO_2-EOR project becoming one of the largest potential CO_2 storage sites in China. The Jilin Oilfield has developed several oil displacement blocks. Among these, the Hei-79 block is the most representative of CO_2-EOR in the Jilin Oilfield. The Hei-79 block is a low-permeability oil reservoir with a sufficient gas source and a reservoir formation pressure exceeding that of CO_2 flooding.[14] The minimum miscible pressure can be developed in the Hei-79 block for CO_2 miscible flooding. The Hei-79 block is in central Songnen Plain, an alluvial low plain with a flat and open terrain and a ground elevation of between 145 m–150 m. The CO_2 test area consists mainly of dry fields and grasslands. The Hei-79 block was put into trial operation in 2010. After one year of continuous gas injection, a mixture of water and gas was injected alternately for eight years, following which supercritical CO_2 was injected. The monitoring of the Hei-79 formation is through well liquid and soil gas.[15] The maximum injection pressure of the CO_2 wellhead can reach 23.3 MPa whereas the maximum daily injection rate is 35 t d^{-1}. The annual injection volume of the Hei-79 formation is 90,000 tons.[16–17]

Method description

Process used in the risk potential matrix

The risk potential matrix transforms evaluation indicators based on the risk matrix. Within the method, hazard refers to the degree of danger generated by the technology and facilities involved in the storage, whereas sensitivity refers to the degree of



Degree	Extremely High Hazard (P5)	High Hazard (P4)	Medium Hazard (P3)	Light Hazard (P2)	Extremely Light Hazard (P1)
Extremely High Sensitive (D5)	V	V	IV	IV	III
High Sensitive (D4)	V	IV	IV	III	II
Medium Sensitive (D3)	IV	IV	III	II	II
Low Sensitive (D2)	IV	III	II	II	I
Extremely Low Sensitive (D1)	III	II	II	I	I

Figure 1. Environmental risk potential matrix.

influence of external factors on environmental receptors (Fig. 1). Risk potential (hazard and sensitivity) is integrated with the risk matrix. A description of risk and the monitoring indicators are used to combine the hazard (exposure) and sensitivity (impact) within qualitative and quantitative risk assessment. This approach improves the assessment of the level of risk of geological storage of CO_2.

As shown in Fig. 2, the process is divided into three steps:

Step 1: Project investigation and risk identification. Data for the site including hydrogeology, infrastructure, technology, and surrounding population are collected. Risks are identified according to the actual state of the construction project, including hazard factors and sensitive receptors.

Step 2: Assessment of potential risk. This process can be divided into two further steps, namely the assessment of hazard and the assessment of sensitivity. The assessment of hazard considers the scale of the project and the actual operating. The possible events (exposure assessment) are determined and the total hazard score is identified according to the category of hazard degree. During the assessment of sensitivity level, the maximum value of the environmental monitoring data collected during the monitoring period is compared with the background value and threshold value to evaluate the impact of environmental receptors (impact assessment) and to classify the level of sensitivity.

Step 3: Risk management. Management strategies are proposed according to the results of the evaluation.

The classification is designed to assist enterprises in effectively dividing the level of risk during the project lifecycle, to minimize the environmental risk, and to minimize the uncertainty.

Method of risk identification

Risk Breakdown Structure (RBS) is derived from Work Breakdown Structure (WBS).[18] RBS describes the identified project risks according to their types and the nature of exposure to engineering risk. RBS systematically divides the identified risks into categories, thereby assisting decision makers in identifying risks from different perspectives. As a general and practical tool, RBS is widely used in risk management at all stages of a project lifecycle. The method can be applied during the risk identification stage or it can provide support during the later stage (risk assessment and risk response).

The present study subdivided risk into hazard and sensitivity under the concept of risk potential. The RBS method was used to reclassify the dispersed risk factors associated with the stage of geological CO_2 storage. The classification of hazard was considered from both

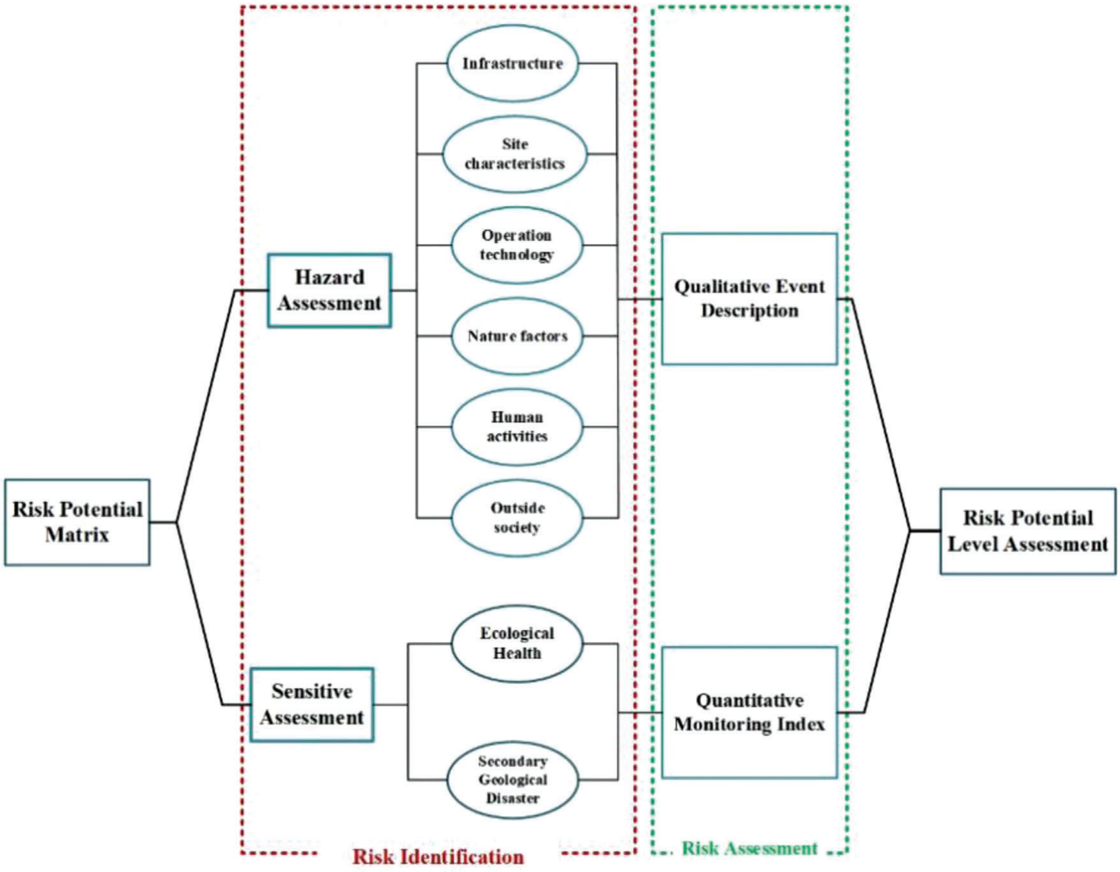


Figure 2. Risk potential matrix assessment process.

above-ground and below-ground perspectives. Above-ground factors considered included facilities, injection parameters, and external human and social factors. Below-ground factors considered included the environment of site storage and natural geological factors. The classification of sensitivity focused on the CO_2 migration path from above ground to below ground and considered the below-ground space, groundwater, soil microorganisms, surface water, and near surface atmosphere. Among these factors, the focus was on below-ground space and groundwater sources of drinking water as indicators of the safety of the geology and drinking water, respectively.

Method of hazard assessment

Hazard elements are divided into four types according to the degree of hazard: (1) direct leakage hazards; (2) indirect leakage hazards; (3) hazards associated with equipment used during the complete capture or absorption process; (4) hazards associated with small devices in direct contact with CO_2. The hazard types (1) to (4) are assigned scores of 10, 5, 2, and 1, respectively. In addition, the two types of storage are assigned additional scores of 5 each since oil displacement involves flammable and explosive hazardous substances and since the use of these technologies for ocean storage poses a challenge[19,20] (Table 2).

The division of scores shown in Table 1 is based on a small-scale storage capacity of 100,000 t a^{-1}. By considering the scales of different projects, the scores assigned to Type 3 and Type 4 during the hazard

Table 1. Hazard P classification (Storage volume of 100 000 t a^{-1}).

Degree of hazard	Hazard level	*P* score
Extremely high hazard	Level 5 (P5)	$P \geq 75$
High hazard	Level 4 (P4)	$65 \leq P < 75$
Medium hazard	Level 3 (P3)	$45 \leq P < 65$
Light hazard	Level 2 (P2)	$40 \leq P < 45$
Extremely light hazard	Level 1 (P1)	$P < 40$

Table 2. Hazard P score.

Category	Sealing type and hazardous facilities	Hazard type	P score
Infrastructure	CO_2 compressor	4	1/Unit
	CO_2 storage tank	4	1/Unit
	CO_2 pump	4	1/Unit
	Trapping device	3	2/Unit
	Absorption device	3	2/Unit
	Pipeline transportation distance	4	1/10 000 m
	Abandoned well[21,22]	1	10/Well
	Storage tank with unstable storage pressure	2	5/Tank
	Injection wells / monitoring wells that have not undergone maintenance for over 3 years	2	5
	During the operation period, the compressor, valve, etc., are out of service or damaged by corrosion	2	5/Time
Site characteristics	Other pipelines exist above the reservoir besides those for gas injection and oil displacement	2	5
	Undetected geological fault[23–25]	1	10
	Caprock thickness is less than 300 m	2	5
	Reservoir porosity $< 10\%$	2	5
	Reservoir permeability $> 5 \times 10^{-3}\ \mu m^2$	2	5
Natural factors	Seismic intensity over the last five years ≥ 7 degrees	1	10
	Seismic intensity over the last five years between 5 to 7 degrees	2	5
	Storage site experiences seasonal frozen soil 26	2	5
	Frequent thermal activity of groundwater	2	5
Technical operations	Injected CO_2 content $< 90\%$	2	5
	The injection rate fluctuates greatly	2	5
	The carbon dioxide injection pressure exceeds the maximum wellhead limit[27]	1	10
	Layer fracture or fault activation[28]	1	10
	Fluid migration error detection[29]	2	5
Human activities	Population activities within a radius of 2 km of the site	2	5
	Artificial mining, drilling, and other activities within a radius of 3 km of the site	2	5
External social factors	Public opposition[30]	2	5–0
	Enterprise capital investment	2	5–0
Special storage	Displacement and storage of natural resources	–	5
	Ocean storage	–	5

assessment will vary with the scale of the project. During large-scale storage, the final score obtained according to Table 2 will be increased due to the increase in infrastructure, resulting in the risk assessment identifying a large risk. Therefore, the scores assigned to Type 3 and Type 4 for other storage scales will be expanded or reduced proportionally. For example, the score assigned to the CO_2 compressor used in a project with a storage capacity of 400,000 t a^{-1} and 16 CO_2 compressors is:

$$\frac{16 \times 1 \times 100\,000}{400\,000} = 4 \tag{2}$$

The assessment of Type 1 and Type 2 remains unchanged.

Method used within the assessment of environmental sensitivity

The leakage of CO_2 is the main factor affecting the sensitivity of environmental receptors. A wide range of leakage channels exist, thereby complicating the assessment of the point of leakage. Therefore, the indirect monitoring index plays an important role in the assessment of the degree of influence of leakage. Environmental receptors of the risk of geological CO_2 storage include the atmosphere, surface water, soil, groundwater, and the reservoir. The sensitivities of these receptors represent the degrees of interference they experience.[31–36] The local atmospheric CO_2 concentration can affect human health and high concentrations over a large area can contribute to global climate change. High CO_2 concentrations in surface water can affect the growth of aquatic organisms and plants and can result in large areas devoid of living organisms in severe cases. Since groundwater is in direct contact with underground minerals and other substances, a change in the quality of groundwater can result in heavy metals dissolving into groundwater to concentrations that exceed the standards.[37] Soil contains a large number of microorganisms. These microorganisms play an important role in crop growth. Acidification of soil can change the mode of growth of microorganisms. In serious cases, this can result in farming land becoming barren and unsuitable for planting. In addition, the pressure of the reservoir during operation determines the CO_2 storage environment. A good storage effect can be guaranteed only when the reservoir pressure exceeds the critical pressure of CO_2. Not achieving this condition can result in instability of the reservoir, which further leads to geological fractures and even earthquakes.[38–40]

The proposed threshold provides a reference for the assessment of the sensitivity of environmental receptors. The threshold of atmospheric CO_2 concentration refers to the CO_2 concentration standards of various countries and the impact of CO_2 on human health. The risk threshold of surface water CO_2 concentration is determined based on the relevant standards combined with threshold for damage to the aquatic ecology. Representative indicators include pH, dissolved oxygen (DO), and chemical oxygen demand (COD). CO_2 enters the underground water layer, resulting in groundwater acidification, which further results in minerals dissolving in groundwater, particularly carbonic acid. The dissolution of salt minerals is intensified and the decrease in pH can result in increased concentrations of some trace metals. Therefore, indicators used for the evaluation of groundwater include pH, total hardness (TH); calculated as $CaCO_3$ (mg L^{-1})], total dissolved solids (TDS), iron (Fe), manganese (Mn), sodium (Na), arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and barium (Ba). The threshold of risk of soil CO_2 is proposed based on the impact of soil CO_2 concentration on the near surface ecology. The impact of atmospheric CO_2 concentration is different for different types of plants. Therefore, the risk threshold of atmospheric CO_2 is proposed based on the response of various types of plants. In addition, the risk threshold for the assessment of secondary geological hazard was identified. Reservoir pressure was selected as the evaluation index and the critical value of CO_2 was used as the threshold.

The use of monitoring data collected over a certain period of time within the assessment can more accurately reflect environmental sensitivity compared to the use of single observations. Therefore, at least 10 days of monitoring data were chosen to predict the sensitivity. Table 3 provides the threshold of environmentally sensitive targets.

Results

Risk identification

Hazard identification

According to the characteristics of Jilin Oilfield CO_2-EOR Hei-79, the RBS method was used to describe the entire lifecycle of CO_2 through the six sub-categories listed in Table 4.

Identification of sensitive receptors

The environmentally sensitive receptors of the Jilin Oilfield CO_2-EOR Hei-79 block were identified according to the CO_2 leakage pathway and environmental impact. These included the atmosphere, groundwater, soil microorganism, and reservoir (Table 5). No surface water bodies were present around the site.

Table 3. Thresholds of environmentally sensitive targets.

Sensitivity evaluation level		Level 1 (D1)	Level 2 (D2)	Level 3 (D3)	Level 4 (D4)	Level 5 (D5)
Environmentally sensitive targets	Monitoring indicators	Extremely light sensitive	Light sensitive	Medium sensitive	High sensitive	Extremely high sensitive
Atmospheric	Near surface carbon dioxide concentration/%	< 0.5	0.5 – 1	1 – 3	3 – 5	> 5
Soil	Near surface carbon dioxide concentration/%	< 10%	15 – 20%	> 20%	20 – 50%	> 50%
Surface water	pH	6.5 ≤ pH < 8.5		5.5 ≤ pH < 6.5 8.5 < pH ≤ 9.0	pH < 5.5 or pH > 9.0	
	DO (mg L^{-1})	6 ≤ DO<7.5	5 ≤ DO <6	3≤ DO<5	2 ≤ DO < 3	< 2
	COD (mg L^{-1})	≤15	15 < COD ≤ 20	20 < COD ≤ 30	30 < COD ≤ 40	> 40
Groundwater	pH	6.5 ≤ pH < 8.5		5.5 ≤ pH < 6.5 8.5 < pH ≤ 9.0	pH < 5.5 or pH > 9.0	
	TH (mg L^{-1})	≤ 300	≤ 450	≤ 650	≤ 900	> 900
	TDS (mg L^{-1})	≤ 500	≤ 1000	≤ 2000	≤ 2500	> 2500
	Fe (mg L^{-1})	≤ 0.2	≤ 0.3	≤ 2.0	≤ 3.0	> 3.0
	Mn (mg L^{-1})	≤ 0.05	≤ 0.1	≤ 1.5	≤2.0	> 2.0
	Na (mg L^{-1})	≤ 150	≤ 200	≤ 400	≤ 500	> 500
	As (mg L^{-1})	≤ 0.001	≤ 0.01	≤ 0.05	≤ 0.10	> 0.10
	Cd (mg L^{-1})	≤ 0.001	≤ 0.005	≤ 0.01	≤ 0.02	> 0.02
	Cr (mg L^{-1})	≤ 0.01	≤ 0.05	≤ 0.10	≤ 0.15	> 0.15
	Pb (mg L^{-1})	≤ 0.005	≤ 0.01	≤ 0.10	≤ 0.15	> 0.15
	Ba (mg L^{-1})	≤ 0.10	≤ 0.70	≤ 4.00	≤ 5.00	> 5.00
Reservoir	Reservoir pressure / Mpa	> 1.6 M	1.4–1.6 M	1.2 – 1.4 M	M – 1.2 M	< M

Note: M is the critical value of carbon dioxide.

Assessment of risk potential

Hazard assessment

Hei-79 CO_2-EOR contains 16 production wells and 10 injection wells composed of corrosion-resistant stainless steel. The wellhead injection pressures of the wells do not exceed 23.3 MPa. The produced gas is separated and purified, following which it is re-injected. Multi-stage compression is used to achieve boosting. The volume of CO_2 injected into each well is 25 t d^{-1}. The gas injection volume reaches 1.6 HCPV (Hydrocarbon Pore Volume) after the project runs.

(1) Infrastructure. Hei-79 currently contains four CO_2 compressors. Low temperature and low pressure conditions of −20 °C and 2.5 MPa, respectively are maintained in six CO_2 storage tanks. There are a total of seven CO_2 pumps comprising four injection pumps and three delivery pumps. There are three sets of capture and absorption processes, respectively. The length of the CO_2 pipeline is 12,600 m. A total of 22 abandoned wells existed before the selection of the site, all of which are now sealed. The interval between well inspections is 5 years. None of the equipment has failed during operation.[47,48]

(2) Site characteristics. The reservoir in Hei-79 is composed of silt sandstone. The porosity and permeability of the reservoir are 13% and 4.5×10^{-3} μm^2, respectively. The thickness of the caprock is 500 m. The pressure and temperature of the oil layer are 24.3 MPa and 94.7 °C, respectively and the pressure coefficient is 0.98. Only CO_2 pipelines and oil and gas

Table 4. Hazard factors identified through risk breakdown structure (RBS).

Classification	Events	Factors
Infrastructure	Wells (Including injection wells, monitoring wells, etc.)[40]	Legacy factors
		Stress factors
		Corrosion factors
		External geological factors
	Storage tank[40]	Stress factors
		Corrosion factors
	Pipeline[40]	Corrosion factors
		Stress factors
		External geological factors
	Capture and absorption devices	Corrosion factors
		Secondary pollution
	Other devices	Failure factors
Site characteristics	Site selection of storage site[50]	Geological factors
	Undiscovered faults[51]	Legacy factors
	Reservoir[41]	Geological factors
	Caprock	Geological factors
Operation technology	CO_2 injection parameters[42]	Planning factors
	CO_2 injection components[43]	Planning factors
	Injection schedule[43]	Planning factors
	Underground pipeline[43]	Planning factors
Natural factors	Earthquake[44]	External geological factors
	Seasonal frozen soil	Climatic factors
	Volcanism and magmatism[52]	External geological factors
	Hydrothermal activity[53]	External geological factors
	Changes in reservoir water content	External geological factors
	Reservoir structure and development status	External geological factors
	Climate change	Climatic factors
Human activities	Underground activities such as mining	Human factor
	Illegal drilling	Human factor
	Illegal construction	Human factor
	Population characteristics and lifestyle[45]	Human factor
	Land and water use	Human factor
Outside society	Public attitude[45]	External factors
	Related policies	External factors
	Enterprise capital investment	External factors

pipelines exist above the reservoir. Normal faults occur in the caprock of Hei-79 and no geological faults have been discovered.[14,47]

(3) Natural factors. The Songliao Basin experiences weak tectonic fault activity and the frequency of strong earthquakes in this area is relatively small. Earthquakes with magnitudes of 6.75 and 5.0 occurred in 1119 and 2006, respectively, although no earthquakes have occurred over the past five years. No seasonal freezing of soil occurs in the Hei-79 test area.[49,50]

Table 5. Identification of environmentally sensitive receptors through risk breakdown structure (RBS).

Classification	Sensitive target
Ecological health	Atmosphere
	Groundwater
	Soil microorganisms
Secondary geological disaster	Reservoir

(4) Operation technology. The injection CO_2 content, stable speed, and pressure are 99.6%, 20 $m^3\ h^{-1}$, and 18.6 MPa, respectively. However, industrial oil is mainly obtained through fracturing during oilfield development. Fracturing has resulted in layer fracturing and fault activation.[14]

(5) Human activities. Human activities occur 3 km away from the site boundary. Illegal drilling and oil theft occurs due to its economic value.[14]

(6) External social factors. The project enjoys good public support. The total investment into this project is $4,450,558 and the company enjoys sufficient capital investment. Relevant policies are well developed.[46]

These potential hazards can increase the risks of CO_2 storage and even result in casualties. Table 6 shows the associated hazard score. The hazard P score of the CO_2-EOR project in Jilin oilfield Hei-79 was calculated to be 56, falling within the P3 medium hazard (Table 1).

Assessment of sensitivity

The environmentally sensitive receptors of the Hei-79 project were monitored for 10 days after injection under normal working conditions. A comparison of the monitoring data with the environmental background value and the environmental threshold shown in Table 3 indicated that the sensitivity indices of the atmosphere, soil, and reservoir fell within the D1 level. Although the contents of iron and manganese in groundwater during the monitoring period fell within the D3 level, so did the environmental background value. This result indicates that the injection of CO_2 does not result in disturbance to the groundwater and the functional level of the groundwater does not decrease. Therefore, the groundwater sensitivity level was identified as D1. Table 7 shows a summary of the monitoring data.

Assessment of the potential level of risk

The hazard assessment determined the total score to be 56. As shown in Table 1, Hei-79 has a hazard level of P3. As shown in Table 3, the sensitivity assessment indicated that each environmental receptor index was at the extremely low sensitivity level D1. In addition, the indices were roughly the same as that before the injection, indicating no CO_2 leak. However, the level of hazard was unacceptable due to the influence of infrastructure, operating technology, and human activities. As shown in Fig. 1, the corresponding level of risk of D1 and P3 was level II (Fig. 3).

Discussion

The risks associated with the CO_2-EOR Hei-79 block of the Jilin Oilfield during the production process were effectively identified through the use of the combination of hazard scores and sensitivity monitoring indicators. The hazards associated with the site geological conditions, climatic conditions, storage conditions before the operation of the project, stability of the infrastructure, stratum characteristics, injection parameters, and external factors during the operation phase were evaluated. The Hei-79 block had overall risk and sensitivity levels of II and I, respectively and each environmental receptor remained in a normal state, indicating no CO_2 leakage. However, the hazard level was III, thereby affecting the overall risk of the project.

The hazard assessment indicated that outside factors posed the largest risk to CO_2 leakage. The permeability and porosity of the reservoir and the thickness of the cap layer will influence the storage effect of supercritical CO_2. The reservoir characteristics of the Hei-79 block are suitable for the permanent storage of supercritical CO_2. The porosity and permeability of the Hei-79 block of 13% and 15%, respectively provides sufficient storage space for supercritical CO_2 and facilitates migration. The thickness of the cap layer of 500 m prevents the upward migration of CO_2.

The existence of geological cracks has a great influence on the storage effect. Industrial oil is mainly obtained from the Hei-79 block through fracturing. This fracturing method can be the direct cause of fractures. The formation of artificial fractures can readily result in activation of faults and even the triggering of new faults. The economic value of oil results in illegal drilling, thereby compromising the long-term storage of CO_2.

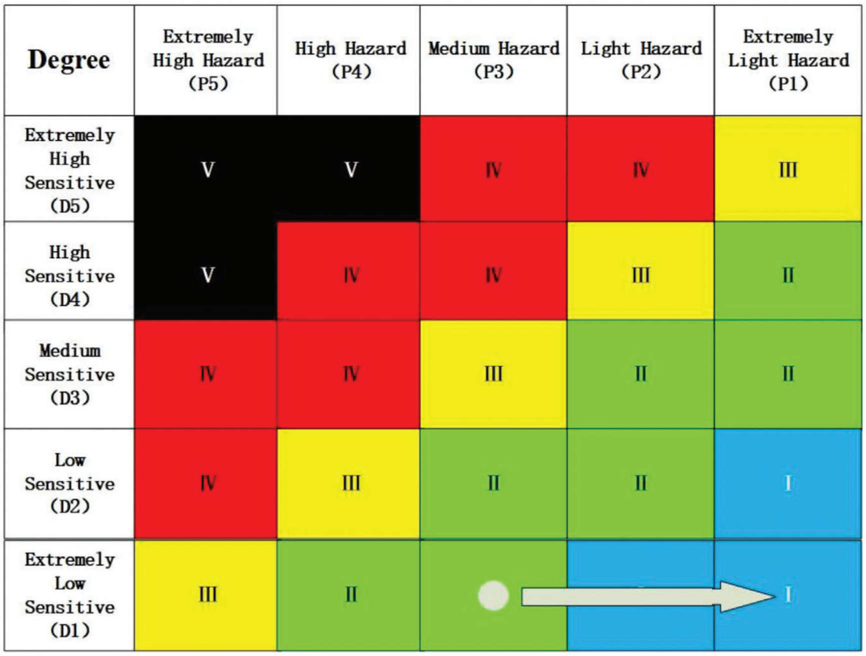
The corrosive nature of CO_2 increases the material requirements of infrastructure. Therefore, timely maintenance of infrastructure is indispensable. However, the excessively long maintenance period of

Table 6. Assessment of the hazard of the CO_2-EOR project in Jilin Oilfield Hei-79.

Category	Sealing type and hazardous facilities	Description	P Score
Infrastructure	CO_2 compressor	Four	4×1
	CO_2 storage tank	Six	6×1
	CO_2 pump	Seven	7×1
	Trapping device	Three	3×2
	Absorption device	Three	3×2
	Pipeline transportation distance/10 000 m	12, 600 m	2×1
	Abandoned well	All 22 abandoned wells in the risk area have been sealed.	0
	Storage tank with unstable storage pressure	The tank pressure is stable at 2.5 MPa	0
	Injection wells / monitoring wells that have not undergone maintenance for over 3 years	The maintenance period of Hei-79 is 5 years	5
	During the operation period, the compressor, valve, etc. are out of service or damaged by corrosion	Failure frequency is zero	0
Site characteristics	Other pipelines exist above the reservoir besides those for gas injection and oil displacement	None	0
	Undetected geological fault	None	0
	Caprock thickness is less than 300 m	Caprock thickness is 500 m	0
	Reservoir porosity $< 10\%$	Reservoir porosity is 13%	0
	Reservoir permeability $> 5 \times 10^{-3}\ \mu m^2$	Reservoir permeability is $4.5 \times 10^{-3}\ \mu m^2$	0
Natural factors	Seismic intensity over the last five years ≥ 7 degrees	None	0
	Seismic intensity over the last five years between 5 to 7 degrees	None	0
	Storage site experiences seasonal frozen soil[26]	None	0
	Frequent thermal activity of groundwater	None	0
Technical operations	Injected CO_2 content $< 90\%$	The carbon dioxide content reaches 99.6%	0
	The injection rate fluctuates greatly	The injection rate is stable at 20 $m^3\ h^{-1}$	0
	The carbon dioxide injection pressure exceeds the maximum wellhead limit[27]	Carbon dioxide injection pressure of 18.6 MPa is less than the maximum wellhead limit of 23.3 MPa	0
	Layer fracturing or fault activation	Fracturing causes layer cracks	10
	Fluid migration error detection	None	0
Human activities	Population activities within a radius of 2 km of the site	Human activities are 3 km away from the boundary of the site	0
	Artificial mining, drilling, and other activities within a radius of 3 km of the site	Illegal drilling within 3 km	5
External social factors	Public opposition	High support rate	0
	Enterprise capital investment	High investment	0
Special storage	Displacement and storage of natural resources	CO_2-EOR	5
	Ocean storage	None	0
Total			56

Table 7. Assessment of the sensitivity of the CO_2-EOR project in the Jilin Oilfield.

Environmentally sensitive targets	Monitoring indicators	Environmental background value	Minimum and maximum values in the monitoring period of 10 days after injection	Sensitivity level
Atmospheric	Near surface carbon dioxide concentration (%)	0.06%	0.04 – 0.08%	D1
Soil	Near surface carbon dioxide concentration (%)	0.0023%	0.002 – 0.004%	D1
Groundwater	pH	7.30	7.30 – 7.31	D1
	TH (mg L^{-1})	274.3	274.3	
	TDS (mg L^{-1})	402	401.5 – 402	
	Fe (mg L^{-1})	0.48	0.48	
	Mn (mg L^{-1})	0.351	0.351	
	Na (mg L^{-1})	< 150	< 150	
	As (mg L^{-1})	0.001	0.001	
	Cd (mg L^{-1})	< 0.0005	< 0.0005	
	Cr (mg L^{-1})	< 0.004	< 0.004	
	Pb (mg L^{-1})	< 0.0025	< 0.0025	
	Ba (mg L^{-1})	< 0.01	< 0.01	
Underground space	Reservoir pressure / Mpa	21	17	D1



Degree	Extremely High Hazard （P5）	High Hazard （P4）	Medium Hazard （P3）	Light Hazard （P2）	Extremely Light Hazard （P1）
Extremely High Sensitive （D5）	V	V	IV	IV	III
High Sensitive （D4）	V	IV	IV	III	II
Medium Sensitive （D3）	IV	IV	III	II	II
Low Sensitive （D2）	IV	III	II	II	I
Extremely Low Sensitive （D1）	III	II			I

Figure 3. Risk potential matrix evaluation of CO_2-EOR project in Jilin Oilfield Hei-79.

the Hei-79 block can result in leakage due to corrosion being overlooked.

The sensitivity assessment proposed an environmental receptor threshold to provide a reference for environmental monitoring indicators. The sensitivity levels of both the atmosphere and soil of the Hei-79 block are low. Although iron and manganese contents of groundwater are too high, they are similar to the environmental background value, indicating that groundwater remains undisturbed and that there is no leakage of CO_2. Moreover, the reservoir pressure far exceeds the critical pressure of CO_2, effectively guaranteeing the long-term storage of CO_2.

Conclusions

The risk potential matrix method combined with hazard scores and environmental monitoring indicators accurately assessed the overall risk level of the Hei-79 block in the Jilin Oilfield. In contrast to previous risk assessments that used a single element, the risk potential matrix method assesses possible risks through specific events and monitoring data from multiple perspectives. The present study optimized the traditional risk matrix method and a reasonable classification system was established. This method is suitable for assessing the risk of storage of different scales and the environmental sensitivity threshold has wide applicability. The hazard level of the Hei-79 block increased the overall risk. Despite there being no leakage of CO_2, measures are necessary to reduce the hazard level.

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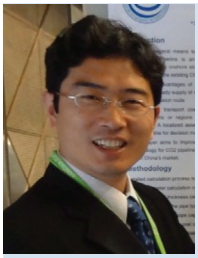

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