

Article

Suitability and Potential Evaluation of Carbon Dioxide Geological Storage: Case Study of Dezhou Subdepression

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Abstract

Under the dual-carbon policy framework, geological CO₂ storage, particularly in saline aquifers, is pivotal to achieving national emission reduction targets. However, selecting geologically favorable storage sites demands quantitative assessment of complex geological factors—a task hindered by subjective traditional methods. To address this, the study employs an integrated approach combining multi-criteria decision analysis (Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation) with multiphase flow simulations to investigate the Dezhou Subdepression in Shandong Province. The results indicate that the Dezhou Subdepression is moderately favorable for CO₂ geological storage, characterized by geologically optimal burial depth and favorable reservoir conditions. When the injection pressure increases from 1.1 times the original Group pressure (1.1P) to 1.5 times the original Group pressure (1.5P), the lateral migration distance of CO₂ expands by 240%, and the total storage capacity increases by approximately 275%. However, under 1.5P conditions, the CO₂ plume reaches the model boundary within 6.3 years, underscoring the increased risk of CO₂ leakage under high-pressure injection scenarios. This study provides strategic insights for policymakers and supports strategic planning for a CO₂ storage pilot project in the Dezhou Subdepression. It also serves as a reference framework for future assessments of CO₂ geological storage potential.

Keywords: carbon dioxide; geological storage; suitability evaluation; containment assessment



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1. Introduction

A century ago, Svante Arrhenius proposed a fundamental model elucidating the relationship between CO₂ concentrations and variations in Earth's surface temperature [1–3]. The greenhouse model was revived in the 1970s due to concerns regarding global warming resulting from escalating emissions of greenhouse gases by industries, combustion of fossil fuels, and alterations in land utilization [4]. The phenomenon of global warming presents a formidable challenge to the natural environment. The mitigation of carbon dioxide (CO₂) emissions represents a shared imperative for all nations worldwide [5,6]. CO₂ geological sequestration technology, recognized by the international community as a direct and effective means of reducing emissions, has garnered attention from governments and scientists worldwide [7]. CO₂ geological sequestration involves the injection of supercritical CO₂ into a secure target reservoir with an effective caprock. The CO₂ is securely stored within the

reservoir through various mechanisms, including tectonic and stratigraphic traps, residual CO₂ traps, solubility traps, and mineral traps [8–10]. Depleted oil and gas reservoirs, uneconomical coal seams, and deep salt groups represent favorable sites for carbon dioxide sequestration [11–13].

To date, carbon neutrality commitments have been made by over 130 countries, as evidenced by recent governmental policy [14]. Being the first among the four major carbon-emitting countries to commit to carbon neutrality, China has made significant strides in domestic deployment of CCUS. According to the annual report of China CCUS, there are approximately 40 operational or under-construction CCUS demonstration projects, boasting a capture capacity of 3 million tons per year, as shown in Figure 1. Among them, there are 13 carbon capture projects encompassing power plants and cement plants, with a cumulative capture capacity of 0.86 million metric tons of CO₂ per year. Additionally, a total of 11 geological carbon utilization and storage (CCUS) projects are currently operational, collectively capable of capturing 1.8 million metric tons of CO₂ annually, with approximately 1.54 million metric tons per year resulting from enhanced oil and gas recovery processes [15]. The latest research findings indicate that the theoretical capacity for CO₂ sequestration in saline aquifers in China ranges from 1.5 to 3.0 trillion tons, representing approximately 96.6% of the total sequestration potential. The sequestration of saline aquifers surpasses that of oil, natural gas, and coalbed methane [16–18]. The main pathway for China to achieve large-scale CO₂ geological storage is through this approach. However, currently only one demonstration project of 100,000 tons per year of sealed storage has been initiated in Ordos City, Inner Mongolia. The development and validation of key technologies are still required for the large-scale implementation of CO₂ sequestration in saline aquifers. These critical technologies requiring further development and refinement include high-precision site characterization techniques, efficient injection engineering methods, long-term monitoring technologies, and predictive modeling and risk assessment capabilities. Addressing these technical bottlenecks is essential for achieving the gigaton-scale, safe, efficient, and verifiable storage necessary to meet climate goals.

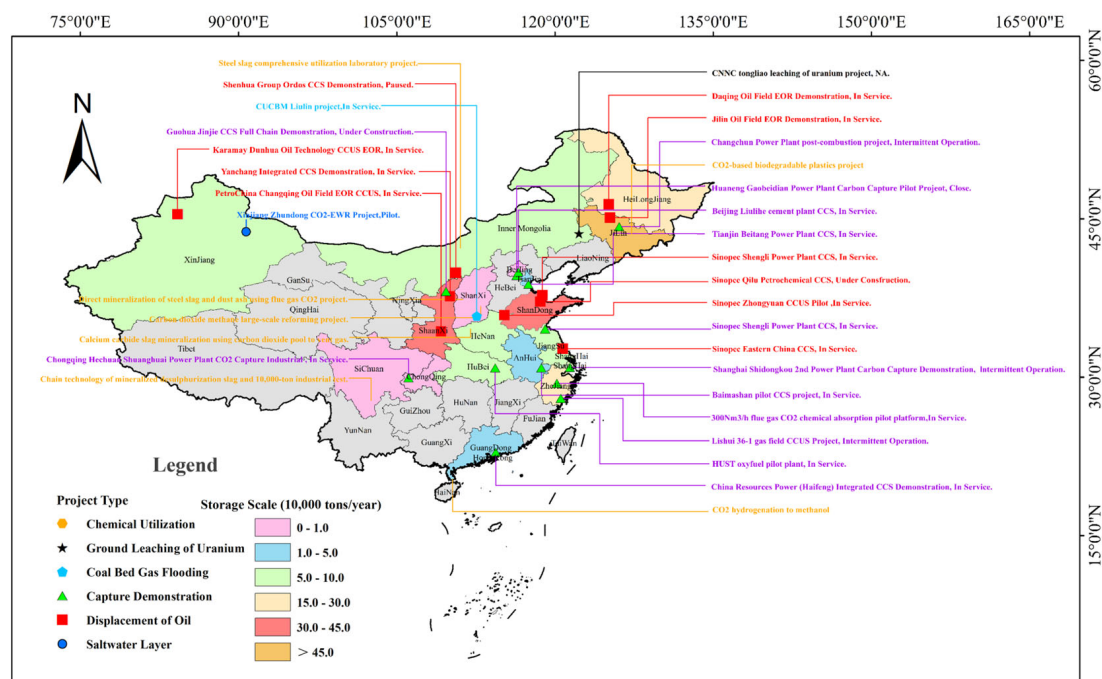


Figure 1. Spatial distribution and development status of carbon capture, utilization, and storage (CCUS) projects in China [7].

With the continuous development of the economy, CO₂ emissions in the Shandong region have been steadily increasing, surpassing 900 million tons annually. This accounts for approximately 9% of national carbon emissions, establishing it as the leading province in terms of carbon emissions. Shandong Province contains a series of extensive sedimentary basins. These basins feature an optimal combination of reservoir and caprock formations, along with well-developed structural traps. As a result, they provide favorable geological conditions for CO₂ storage. Research on CO₂ sequestration in sedimentary basins remains at an early stage. Current studies primarily focus on geological reservoir characterization, storage mechanisms, process simulations, site suitability evaluations, and injection engineering and monitoring [19,20]. Currently, there is a lack of substantial research investigating the geological storage characteristics and sequestration suitability of CO₂ in deep saline aquifers. Therefore, evaluating the suitability of CO₂ geological storage in sedimentary basins with carbon sequestration potential is essential. The goal is to identify favorable sites for CO₂ sequestration [21–24]. China's 'dual carbon target' aims to achieve carbon peaking by 2030 and carbon neutrality by 2060. This will be advanced through optimizing the energy mix and technological innovation to drive green and low-carbon development, supporting global climate governance. Developing a comprehensive evaluation index system and applying modern geological theories are essential steps toward achieving China's "dual carbon" goals. This can be accomplished through the widespread implementation of CO₂ geological storage technology.

This study selected the Dezhou Subdepression as the research area. The Dezhou Subdepression is located in the northwestern part of Shandong Province, bordering Hebei Province. It spans parts of the Dezhou and Liaocheng administrative regions. The primary strata of the deep saline aquifers below 800 m in the study area comprise the Guantao Group, Dongying Group, and Shahejie Group. The group distribution is continuous and stable, without any missing group. The Guantao Group and Dongying Group serve as the primary geothermal reservoirs for development and utilization, yet they are unsuitable as CO₂ sealing and storage layers within saline aquifer groups. The Shahejie Group is extensively developed, primarily composed of clastic rocks. Currently underutilized, it possesses potential as a geological reservoir for CO₂ storage. The overlying Dongying Group is primarily composed of mudstone. It exhibits a uniform distribution and remarkable stability. These characteristics make it suitable as an impermeable geological caprock for CO₂ storage. Therefore, the geological conditions in the Dezhou Subdepression make it a suitable candidate for CO₂ sequestration through geological storage.

The feasibility of sequestration depends on the interaction of multiple geological and socio-economic factors. These include regional scale, structural integrity, geothermal properties, storage conditions, and proximity to carbon emission sources [16,25]. Currently, in the assessment of sealing suitability both domestically and internationally, commonly employed evaluation methods include Analytic Hierarchy Process [26], Expert Survey Method [27], and Expert Experience Judgment Method [28,29]. The subjective weighting method can effectively capture decision makers' subjective preferences, while remaining straightforward and applicable in practice. However, the lack of stability and objectivity in the constructed weights arises from variations in subjective judgment criteria among decision makers. Several studies have been conducted on suitability assessment using objective weighting methods, such as entropy weighting [30], decision making and experimental approaches [31]. The objective weighting method is devoid of subjective randomness and does not impose additional cognitive burden on decision makers, while yielding results that are firmly grounded in theory and mathematics. However, this weighting method depends on the specific problem domain and does not consider the subjective intentions of decision makers. Consequently, it limits generality and reduces decision-maker participa-

tion. Additionally, it introduces computational complexity. CO₂ geological sequestration itself involves numerous intricate and uncertain factors. The classification and determination of evaluation index levels are characterized by ambiguity. The Analytic Hierarchy Process (AHP) seamlessly integrates qualitative and quantitative methodologies, enabling the systematic simplification of complex problems. Additionally, the fuzzy comprehensive evaluation method adeptly handles ambiguous evaluation objects and facilitates a more rational quantification of fuzziness in groups. Therefore, the Analytic Hierarchy Process (AHP) is employed for determining the weightage of indices, while integrating the Fuzzy Comprehensive Evaluation method to compute the membership of each evaluation level, thereby assessing the suitability of CO₂ sequestration in the Dezhou Subdepression.

The assessment of sequestration potential primarily encompasses two facets: suitability evaluation and capacity estimation. Various calculation methods are employed to estimate the geological sealing capacity of different media types. These methods include the material balance method, effective volume method, dissolution mechanism calculation, and a comprehensive approach that integrates multiple capture mechanisms [32,33]. These methods fail to adequately account for site-specific conditions and rely solely on geological reservoir space for estimation, resulting in inaccuracies in sequestration capacity assessment. To more accurately estimate the actual strata and sequestration potential, considering perfusion capacity, this study employs a numerical simulation method. The simulation is based on site-specific data from the study area to calculate CO₂ sequestration potential [34–41].

Although numerous studies have explored CO₂ geological storage potential using various assessment methods, they are often constrained by several limitations, including the concentration on large-scale basins, oversimplified evaluation frameworks, and the lack of effective integration between suitability assessment and dynamic storage estimation. This study addresses these gaps by combining AHP-fuzzy comprehensive evaluation with TOUGH2 numerical simulation, which enables a more systematic consideration of both expert judgment and geological uncertainty during site suitability analysis, while quantitatively estimating storage capacity under variable injection conditions. Moreover, the integrated workflow developed in this study is directly applicable to practical engineering, providing technical support for site selection, capacity optimization, and injection scheme design in actual CO₂ storage projects. The detailed workflow is illustrated in Figure 2.

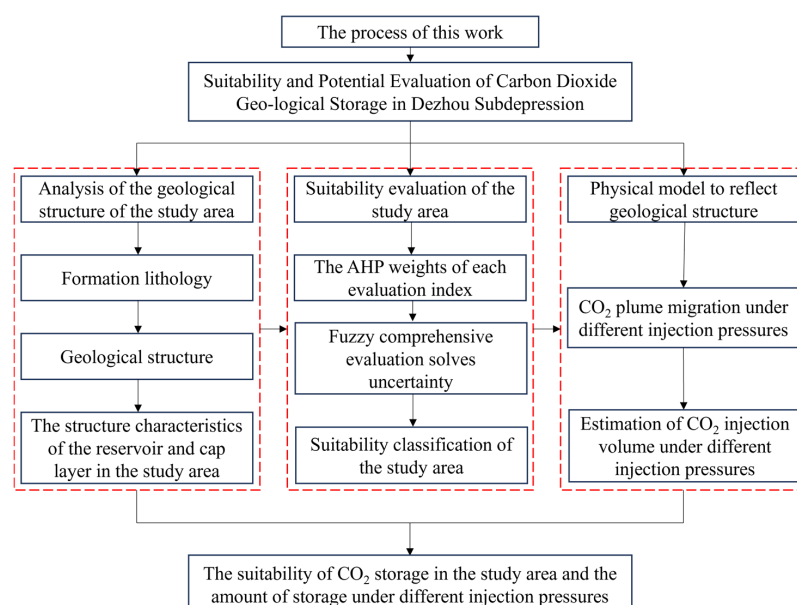


Figure 2. The workflow chart of this research.

2. Study Area

2.1. General Situation of Physical Geography

The Dezhou Subdepression is situated in the northwestern region of Shandong Province, adjacent to Hebei Province (Figure 3). The western and northwestern boundary is demarcated by the Cangdong fault, while the northeastern boundary is delineated by the Bianlinzhen-Yangerzhuang fault. The administrative division encompasses portions of Liaocheng and Dezhou, spanning from $115^{\circ}23'34''$ to $116^{\circ}39'30''$ E and from $36^{\circ}25'58''$ to $37^{\circ}39'48''$ N. The study area encompasses an expanse of 0.34×10^4 km². The study area is situated in a warm temperate semi-arid monsoon climate zone, which is significantly influenced by the monsoon and exhibits distinct continental climate characteristics. The major rivers in the region include the Yellow River, Tuhua River, Dehui Xinhe River, Majia River, and Wei Canal, exhibiting a predominant southwest to northeast flow direction.

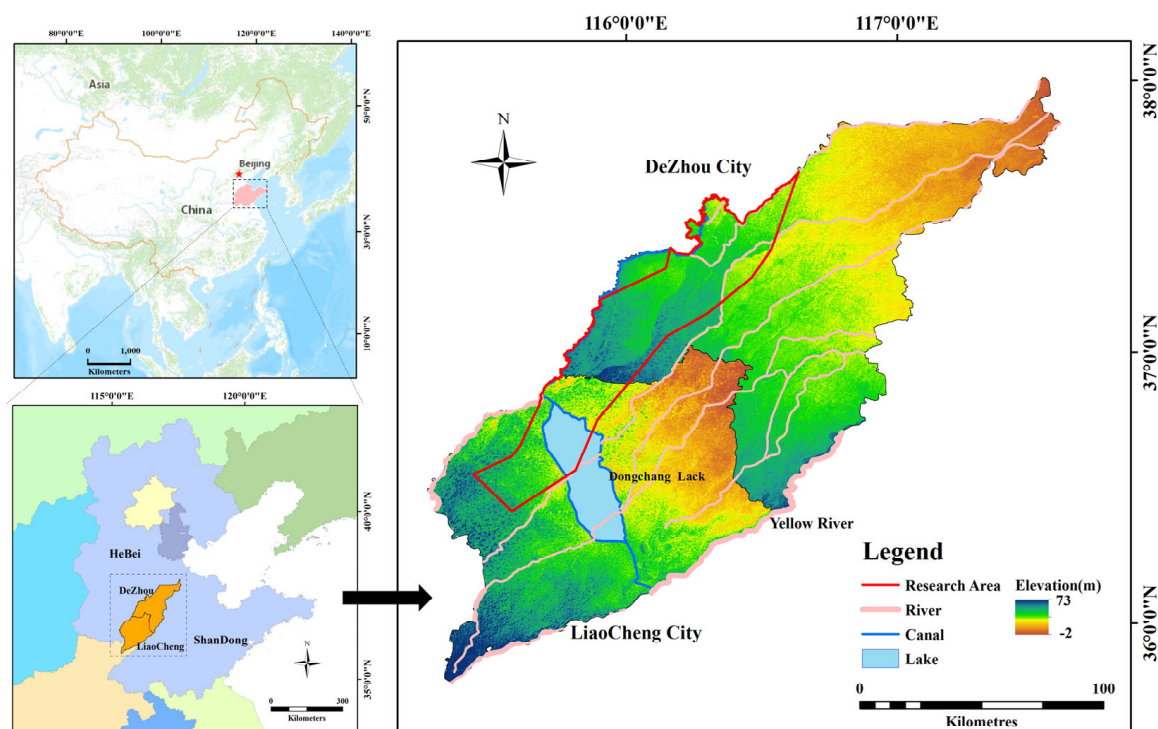


Figure 3. Location map of the study area.

2.2. Stratigraphic Characteristics

The sedimentary patterns exhibit cyclicity as a consequence of Himalayan movement. Distinct sedimentary cycles are influenced by the paleoenvironment, giving rise to a succession of diverse lithologic assemblages. The Cenozoic is well developed, and the strata from new to old are Holocene Series (Q₄) silt or silty clay with silt layer, Quaternary System Pleistocene Series (Q₁, Q₂, Q₃) clay, silty clay with sand layer; Neogene Minghuazhen Group (N₂m) sandy mudstone and fine sandstone, Guantao Group (N₁g) conglomerate, sandstone and sandy mudstone; Paleogene Dongying Group (E₃d) sandstone and mudstone interbedding, Shahejie Group (E₂₋₃s) mudstone with limestone, sandstone and mudstone interbedding, mudstone, sandstone, Kongdian Group (E₁₋₂k) sandstone and mudstone interbedding, mudstone, oil shale and basalt (Figure 4).

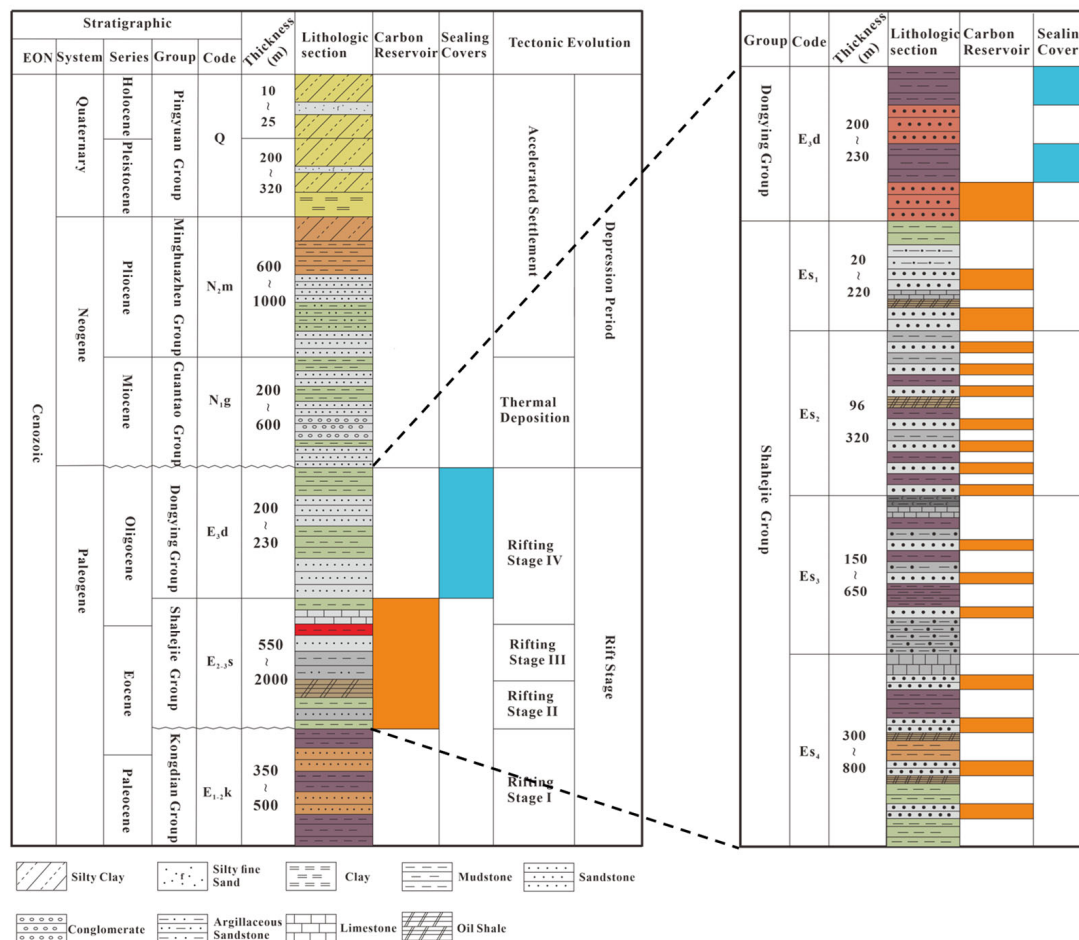


Figure 4. Integrated stratigraphic column and reservoir caprock characteristics.

2.3. Reservoir Caprock Characteristics

The Dezhou Subdepression is situated in the southern region of the North China Plain. The study area is located at the intersection of the Cangxian, Chengning, and Luxi uplift zones. It also lies at the convergence of the Huanghua, Linqing, and Jiyang depression zones within the geotectonic unit. The faulted basin is bidirectional and formed against a backdrop of uplift, spreading in the NE direction. Due to the extensive and intricate forces at play, numerous secondary tectonic units with both positive and negative characteristics are generated within the basin. The Cenozoic strata exhibit considerable thickness, with well-developed Mesocene and Neogene strata playing a pivotal role in the group of multiple reservoir cap assemblages (Figure 4). The Dezhou Subdepression exhibits a widespread distribution of reservoirs, encompassing sandstones and argillaceous sandstones from the Shahejie Group. The sandstone reservoirs consist primarily of sedimentary sandstones exhibiting shallow lake reduction facies, shallow lake facies, river facies, and shallow lake–semi-deep lake facies. The sandstone reservoir exhibits a porosity range of 14–22% and a permeability ranging from 14.89 to 671.78 mD. The pumping test conducted in the research area resulted in a 20 m decrease in depth, accompanied by a water inflow rate of 560 m³/d and a salinity level of 30.61 g/L. The chemical composition of the water was identified as Cl-Na type. The reservoir exhibits favorable properties for fluid storage and flow. The area is characterized by the presence of a well-developed thick mudstone from the Dongying Group, which exhibits potential as a regional cap rock. The mudstone cap rock predominantly consists of fluvial-deltaic sedimentary mudstone, exhibiting continuous and stable characteristics that encompass the entire depression. The thickness of individual

mudstone layers generally exceeds 2.5 m, with a cumulative thickness surpassing 100 m. This constitutes a significant assemblage of regional cap rocks within the Dezhou Subdepression. Based on the distribution characteristics of reservoir and cap rock assemblages, the Dezhou Subdepression exhibits a highly effective combination of reservoir and cap rock assemblages. The Shahejie Group sandstone and argillaceous sandstone exhibit favorable reservoir characteristics, while the Dongying Group mudstone demonstrates excellent cap rock properties (Figure 5).

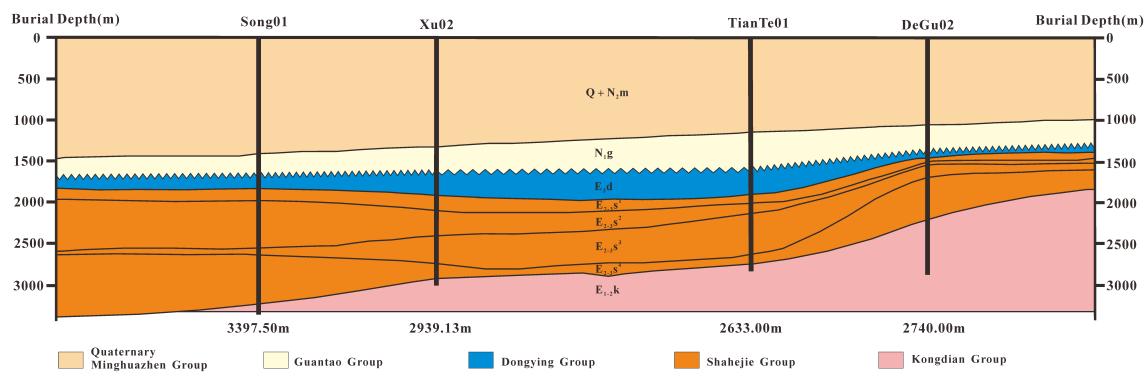


Figure 5. Integrated stratigraphic column and reservoir caprock characteristics in Dezhou subdepression.

2.4. Geological Structure

The study area is located within the Dezhou Subdepression (I_{b2}^1), which is part of the North China Plate-North China Depression (I)-Linqing Depression (I_b)-Dezhou buried fault depression (I_{b2}). The faults in the area with high activity intensity are well-developed, primarily consisting of the Cangdong fault and the Bianlinzhen-Yangerzhuang fault. The Cangdong Fault, which was formed during the Mesozoic era, exhibits an NNE trend and SE dip. The Cangdong fault serves as the boundary fault between the three-tiered tectonic unit of Cangshan uplift and Huanghua and Linqing depressions, exerting control over the development of Paleogene strata. The Bianlinzhen-Yangerzhuang fault zone, which originated during the Mesozoic era, exhibits a NE striking orientation and NW dipping inclination. This fault zone serves as the boundary between the Chengning uplift and the Linqing and Huanghua depressions.

2.5. Characteristics of Geothermal Field

The geothermal gradient value in the study area ranges from 3.2 to 4.0 °C/100 m, exhibiting spatial variability within this range. The geothermal gradient contour line exhibits a consistent NNE trend, which aligns well with the underlying basement structure in the region. The distribution of geothermal gradient in the cap rock is evidently governed by the geological structural pattern. In the area characterized by a forward structure, the bedrock is shallowly buried, resulting in a substantial geothermal gradient within the cap rock. The bedrock in the negative tectonic zone is deeply buried, resulting in a small geothermal gradient of the cap rock. The geothermal gradient of the cap rock is typically below 3.4 °C/100 m in the sag where the basement is deeply buried.

3. Methods

This study assesses the geological potential for CO₂ sequestration in the Dezhou Subdepression, located in Shandong Province, by considering the actual geological conditions. The suitability of CO₂ sequestration was assessed using the analytic hierarchy process and fuzzy comprehensive evaluation method, while the amount of CO₂ sequestration was determined through numerical simulation.

3.1. Data Source

This study utilizes data from regional deep gravity, aeromagnetic, and seismic surveys, as well as oil and geothermal drilling conducted by geological, mining, and petroleum systems. Additionally, relevant published literature from the study area is incorporated.

Furthermore, to comprehensively analyze the potential for CO₂ geological sequestration and its spatiotemporal evolution within reservoirs, obtaining precise parameters is essential. This prerequisite ensures the reliability and accuracy of simulation and prediction results. In this study, a chamber test was conducted using cores from a perfusion well in the geological storage test of the CO₂ salt water layer in Dezhou. The well is situated in Tianqu New District, Dezhou City, Shandong Province, with the geographical coordinates of the well point being 116.31° E and 37.47° N. The test well has a depth of 1700 m, with core samples primarily extracted from the Dongying Group and Shahejie Group. The test quantified key physical properties of the actual site, including porosity, permeability, rock's specific heat capacity, specific surface area of rock, CO₂ water displacement process curve, and mineral composition of rock sample.

3.2. Evaluation Method

The Analytic Hierarchy Process (AHP) is a systematic and hierarchical analysis approach that combines qualitative and quantitative methods for making national macroeconomic decisions. It was initially developed by the University of Pittsburgh in the early 1970s and introduced to China in the early 1980s [42,43]. The fuzzy comprehensive evaluation method (FUZZY) is a robust evaluation approach grounded in the principles of fuzzy mathematics. By leveraging the membership degree theory, this method quantifies qualitative evaluations and provides a comprehensive assessment of objects under various influencing factors [44,45]. The AHP-FUZZY method integrates the weighting of indices and evaluation methods to leverage the complementary advantages of each approach, thereby yielding a more readily applicable evaluation outcome. The procedural steps of the AHP-FUZZY method are as follows:

(1) Determine the evaluation index system

Establishing objectives, examining various influencing factors, elucidating their internal interconnections, and employing structural levels to illustrate the interaction among these factors.

(2) Constructing a Judgement Matrix

The relative significance of each level and factor is quantified using a numerical scale ranging from 1 to 9, and presented in the form of a matrix. The relative importance of index B_i and index B_j can be denoted as B_{ij} in the judgment matrix presented in Table 1.

$$B_{ji} = \frac{1}{B_{ij}} > 0, B_{ii} = 1 \quad (1)$$

where B_{ij} and B_{ji} represent the relative degrees of importance between two indicators.

(3) Calculate the weight of each index

Compute the n -th root of the product of each row in the matrix, yielding an n -dimensional vector $(\bar{W}_i)$, which is calculated using Equation (2).

$$\bar{W}_i = \sqrt[n]{\prod_{j=1}^n B_{ij}} \quad (2)$$

The vector is normalized to serve as the weight vector, and the weight (W_i) is derived using Equation (3).

$$W_i = \frac{\bar{W}_i}{\sum_{i=1}^n \bar{W}_i} \quad (3)$$

Table 1. Evaluation index system of CO₂ geological sequestration suitability.

Indicator Layer	Weight	Sub-Indicator Layer	Weight	Indicator	Weight
Geological safety	0.4761	Regional crustal stability	0.3091	Peak seismic acceleration	0.0311
				Historical seismicity	0.0697
				Active fault	0.2083
		Capping capacity	0.1328	Depth of cover layer	0.0441
				Cap lithology	0.0249
				Cap thickness	0.0257
				Cap continuity	0.0381
		Hydrogeological condition	0.0342	Hydrodynamic action	0.0214
				Degree of mineralization	0.0128
Storage capability	0.4523	Building element size	0.0739	Area of tectonic unit	0.0469
				Deposition thickness	0.0270
				Reservoir depth	0.0678
		Reservoir	0.1343	Reservoir thickness	0.0359
				Reservoir lithology	0.0160
				Porosity	0.0103
				Permeability	0.0043
		Geothermal condition	0.2441	Ground temperature	0.1607
				Geothermal gradient	0.0834
Environmental and economic conditions	0.0716	Social environment	0.0339	Population density	0.0191
				Land use type	0.0148
		Economic condition	0.0377	Carbon source quantity	0.0214
				Carbon source distance	0.0163

(4) Consistency checking

The maximum eigenvalue $\lambda_{\max}$ of the judgment matrix is calculated using Equation (4), while Equation (5) is employed to determine the consistency index (CI).

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{W_i} \quad (i = 1, 2, \dots, n) \quad (4)$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (5)$$

where n is the order of the judgment matrix; AW is the cumulative value of the normalized weights of the judgment matrix in rows.

The test consistency ratio (CR) is calculated by Equation (6).

$$CR = \frac{CI}{RI} \quad (6)$$

where RI is the random consistency index, with RI values corresponding to different orders n ; when $CR < 0.10$, the judgment matrix satisfies consistency.

(5) Fuzzy matrix is constructed by fuzzy comprehensive evaluation method

According to the current situation of the Dezhou Subdepression and the specific requirements of the evaluation task, a five-tier classification system has been established for the evaluation criteria: suitable, more suitable, generally suitable, less suitable, and unsuitable. The membership degree of each index is determined through fuzzy statistics, and the resulting fuzzy matrix $\mathbf{R}$ is obtained after normalization.

$$\mathbf{R} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \quad (7)$$

The weights of all elements $\mathbf{W}$ and the fuzzy matrix $\mathbf{R}$ are consistently manipulated to derive the fuzzy comprehensive evaluation set $\mathbf{B}$, as illustrated in Equation (8).

$$\mathbf{B} = \mathbf{W} \times \mathbf{R} = (w_1, w_2, \dots, w_n) \times \begin{bmatrix} r_{11} & \cdots & r_{12} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} = (b_1, b_2, \dots, b_n) \quad (8)$$

where b_j is the membership degree of the suitability of CO_2 sequestration to the j -th suitability degree in the judgment domain.

(6) Analysis of comprehensive evaluation results

The corresponding score is assigned to each level of the fuzzy comprehensive evaluation set $\mathbf{B}$. The total score x_i is calculated using the weighted scoring method based on the membership degree in the evaluation set, as illustrated in Equation (9).

$$x_i = \sum_{j=1}^n b_j \times p_j \quad (9)$$

where x_i is the comprehensive score of the suitability of CO_2 sequestration of the i -th evaluated object, and p_j is the corresponding score of the j -th suitability degree.

The AHP framework integrated five critical parameter categories for storage suitability assessment: (1) Natural Geographical Features (e.g., elevation, distance to protected areas), (2) Geological Structural Stability (e.g., fault density, seismic activity), (3) Reservoir Properties (e.g., net thickness, depth, temperature), (4) Caprock Integrity (e.g., thickness, continuity, lithology), (5) Hydrogeological Conditions (e.g., salinity, hydraulic gradient). Pairwise comparisons were performed by expert elicitation to assign weights to these categories and their sub-criteria.

3.3. Calculation of CO_2 Sequestration Capacity

Prior to the implementation of a CO_2 geological sequestration project, it is imperative to assess the site's potential for sequestration. This study will employ numerical simulation methods to calculate the potential for CO_2 sequestration, based on actual site data obtained from the study area. The software TOUGHREACT TOUGH2, developed by Lawrence Berkeley National Laboratory, was employed in this study. The software simulates the coupled processes of subsurface multiphase fluid flow and geochemical migration. Its primary applications include CO_2 geological utilization and storage, underground nuclear waste disposal, geothermal energy development and utilization, petroleum extraction, groundwater pollution remediation, and other related fields. It has gained extensive usage in addressing various geological and environmental challenges [37–40]. The TOUGHREACT software package provides a range of modules tailored to address specific challenges, with the ECO2N module being extensively utilized in the realm of deep saline water CO_2 geological sequestration.

4. Results and Discussion

4.1. Suitability Evaluation for Geological Storage of CO_2

The suitability of the geological structure in the Dezhou Subdepression was assessed using the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation method.

This assessment was based on established CO₂ geological sequestration evaluation methodologies applied both domestically and internationally [26,46–51]. The evaluation results were standardized and the suitability was graded based on these results.

4.1.1. Index Weight (AHP)

The Analytic Hierarchy Process (AHP) is a systematic analytical method developed based on qualitative approaches, utilized for quantitatively determining the weightage of each factor in an evaluation. This approach facilitates the quantification of individuals' experiences, enabling a more rigorous and objective evaluation.

Based on a comprehensive analysis of the Dezhou Subdepression's characteristics and previous research on carbon sequestration, site selection evaluation, and CO₂–fluid–rock interactions, four indicator layers—geological safety, storage capacity, environmental conditions, and economic factors—were selected to assess the suitability of carbon sequestration in the Dezhou Subdepression. Each indicator layer comprises multiple sub-indicator layers, while each sub-indicator layer encompasses numerous indicators. These encompass deterministic indicator factors, such as reservoir and cap rock depth, alongside uncertain indicator factors like the influence of earthquakes and active faults (Table 1). The evaluation criteria for CO₂ geological sequestration suitability are categorized into five levels, denoted as A, B, C, D, and E, respectively, representing suitability, relatively high suitability, moderate suitability, relatively low suitability, and low suitability. The scores 21, 15, 7, 3, and 1 are assigned to represent distinct states of the indicators that cannot be quantified.

The evaluation system of this study comprises three indicator layers, eight sub-indicator layers, and twenty-two indicators. The procedure for computing weights through the analytic hierarchy process is as follows:

- (1) Revealing the interrelationships among various factors within the system and establishing a hierarchical framework for the system. The system in this study is categorized into three hierarchical levels: the indicator layer, sub-indicator layer, and indicator.
- (2) The significance of each factor is equitably compared, and a judgment matrix is constructed to facilitate the comparison between two factors.
- (3) The weights of each index layer and sub-index layer were computed, and the corresponding results are presented in Table 1. Subsequently, the consistency of the obtained outcomes was assessed.

The consistency ratio of the index layer comparison judgment matrix is 0.0025 (<0.1), indicating a high level of consistency. By synthesizing judgment matrices from multiple experts, this approach mitigates the impact of individual subjectivity. The weights or ranking results derived from the Analytic Hierarchy Process (AHP) are then compared against actual case studies or historical data to validate their empirical validity and logical consistency.

4.1.2. Fuzzy Comprehensive Evaluation of Suitability

Based on the characteristics of CO₂ geological reserves in the Dezhou Subdepression, a fuzzy comprehensive evaluation method was employed to assess the suitability of this area for CO₂ exploration. The fuzzy comprehensive evaluation method is a holistic approach that employs principles of fuzzy mathematics to assess factors and phenomena influenced by multiple variables. The fuzzy transGroup theory and maximum membership degree are employed to comprehensively assess the factors. The process of fuzzy comprehensive evaluation primarily consists of two steps: (1) constructing a precise fuzzy membership function, and (2) calculating the degree of membership and establishing a judgment matrix. In this study, the trapezoidal distribution was employed in the fuzzy distribution method to construct the membership function of the index and calculate its degree of membership.

In this study, the membership degree is generated using the cloud model. The qualitative-to-quantitative conversion is achieved through a one-to-many mapping approach, which mitigates errors associated with the membership function calculation. The abscissa represents the value of the evaluation index, while the ordinate signifies the degree of membership. An evaluation process can be conducted based on the cloud model. The first step involved the calculation of three numerical features (Ex, En and He) using MATLAB R2022a, as illustrated in Figure 6, to generate the necessary cloud droplets. Subsequently, membership degrees are derived from the proposed cloud generator.

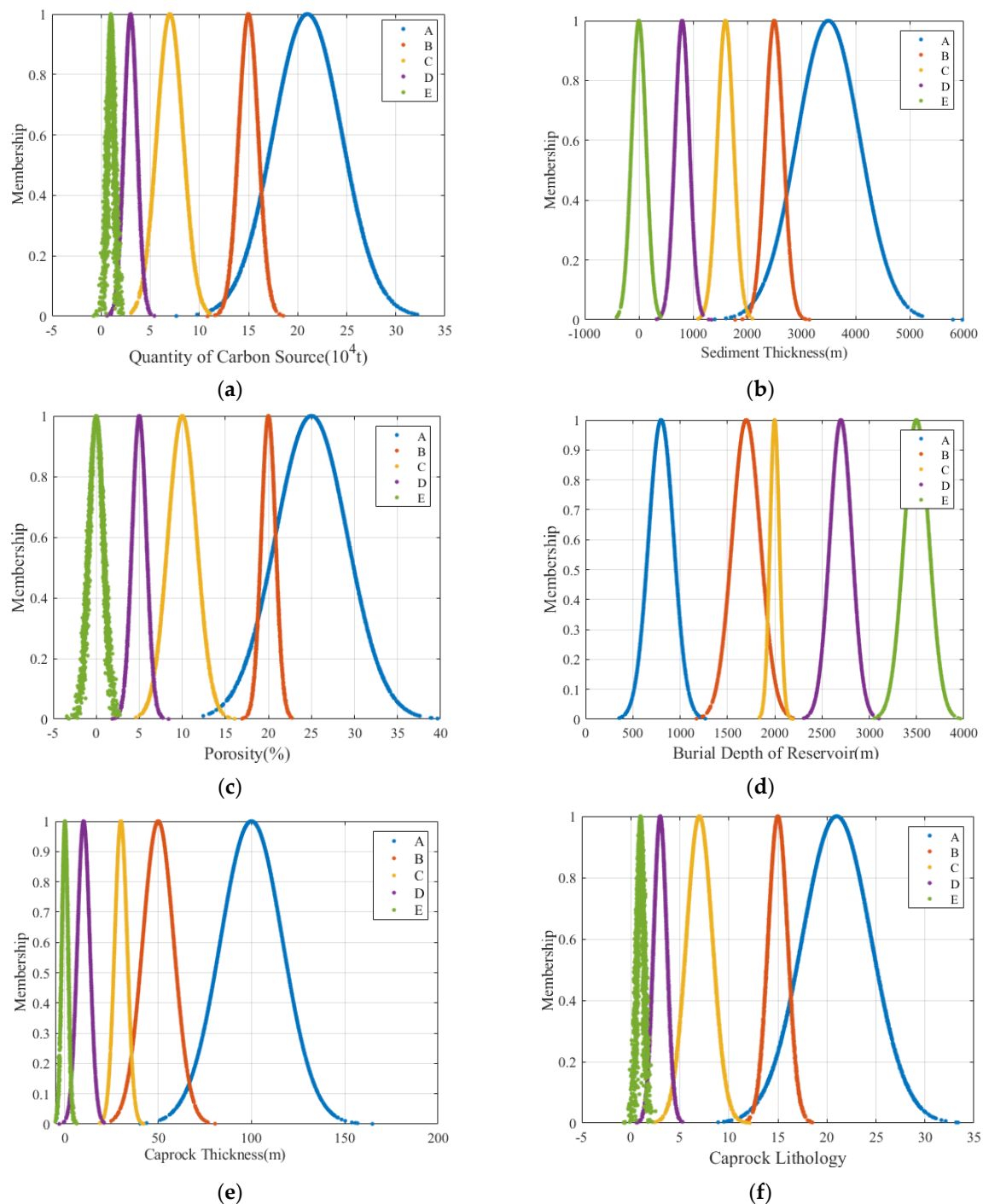


Figure 6. Illustrates cloud maps depicting the standards of evaluation indexes corresponding to each level. (a) Quantity of carbon source. (b) Sediment thickness. (c) Porosity. (d) Burial depth of reservoir. (e) Caprock thickness. (f) Caprock lithology.

The evaluation results were normalized to derive the membership degree of carbon sequestration suitability, as illustrated in Table 2. According to the maximum membership degree principle of fuzzy mathematics, the suitability of CO₂ geological sequestration in the Dezhou Subdepression is relatively suitable, so it is a better CO₂ geological sequestration structure.

Table 2. Membership degree of CO₂ geological sequestration suitability obtained.

Suitability Class	A	B	C	D	E
Membership	0.0794	0.6140	0	0	0.3066

4.2. CO₂ Storage Calculation by Numerical Simulation

4.2.1. CO₂ Geological Reservoir Conditions

CO₂ geological storage involves injecting purified carbon dioxide—separated from centralized industrial emission sources—into deep, sealed underground strata. The geological sequestration of CO₂ necessitates adherence to specific geological prerequisites, including the provision of adequate storage capacity, a well-sealed geological structure, a stable burial medium, and surrounding rock groups. In addition to achieving effective storage outcomes, it is imperative to prevent the occurrence of secondary disasters and minimize the potential risks associated with leakage.

In the process of geological storage of CO₂, injection of supercritical CO₂ into the reservoir is a common practice. The critical point for supercritical CO₂ occurs at 7.38 MPa and 31.1 °C, which can only be attained at depths below 800 m beneath the surface. The reservoir must possess favorable porosity and permeability in order to satisfy the requirements of CO₂ injection and migration. Supercritical CO₂, being less dense than water, exhibits upward seepage through the pores upon injection into the subsurface. The reservoir must be securely covered with a dense cap to effectively mitigate the release of CO₂ into the environment.

The deep saline aquifer is composed of sedimentary rocks rich in salt water, and the groundwater has a high salinity, so it is not suitable for drinking water. The wide distribution of the aquifer is a favorable place for carbon dioxide sequestration. Meanwhile, carbon dioxide exhibits solubility in water and reacts with ions in both the water and surrounding rocks. This process enhances long-term carbon dioxide sequestration in the formation and improves storage capacity.

4.2.2. Model Building and Boundary Condition Setting

Given the limited availability of geological baseline data, a two-dimensional radial model was developed using the TOUGHREACT software. The modeled interval spans from 1463 m to 1614 m and comprises interbedded sandstone and mudstone units of the Dongying and Shahejie Group, as shown in Figure 7a. The group was vertically discretized into 32 equally spaced layers, each 2 m thick. Owing to the radial symmetry of the model around the injection well, only half of the domain was simulated to reduce computational expenses. Laterally, the model domain was divided into 221 grid blocks following a logarithmic increment scheme. To enhance resolution near the wellbore, a non-uniform rectangular mesh was applied, with finer grid spacing closer to the injection well. The wellbore radius was set to $R = 0.2$ m, with the lateral domain further discretized into 100 grid blocks from 0.2 m to 100 m, 80 grid blocks from 100 m to 300 m, and 40 grid blocks from 300 m to 2000 m, as shown in Figure 7b. Time discretization was implemented via an adaptive time-stepping approach, beginning with an initial time step of 1 s and allowing for a maximum time step of 12 h. To simulate the injection system, five virtual well grid blocks were assigned to the left boundary of the model. These blocks are vertically aligned

and hydraulically connected to both the reservoir and caprock layers, serving as conduits for the injection of supercritical CO₂.

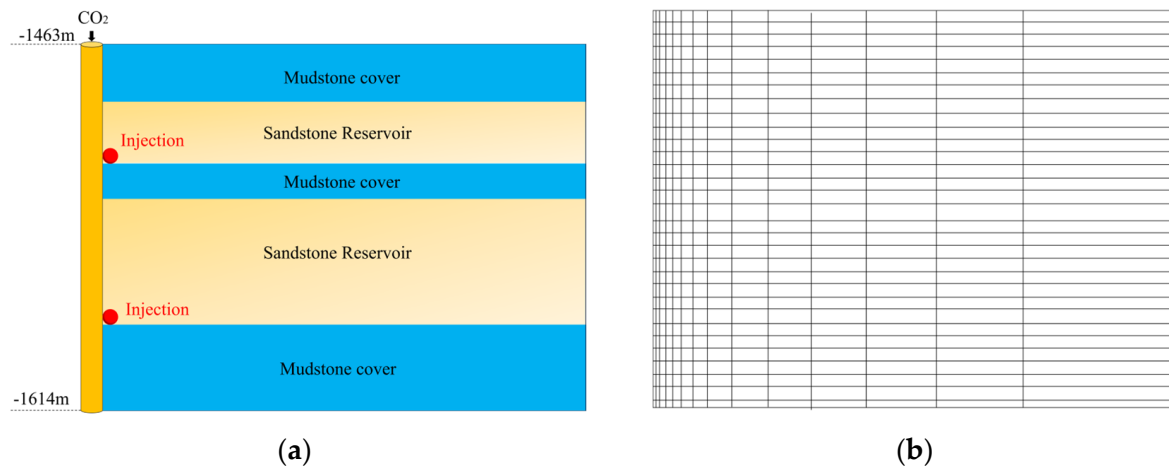


Figure 7. Conceptual model and grid division of numerical simulation. (a) Conceptual model. (b) Mesh partition.

Temperature and pressure variations at radial infinity are considered negligible; therefore, a Dirichlet-type boundary condition with fixed values was applied to the outer radial boundary. The top and bottom boundaries, representing the low-porosity, low-permeability mudstone caprock and the underlying basement, were treated as Neumann-type (no-flow) boundaries. Similarly, the left boundary of the model—except at the injection well—was assigned a zero-flux Neumann condition, reflecting both physical symmetry and hydraulic isolation from adjacent groups. Based on actual field injection parameters, perforations were created at two reservoir intervals, enabling CO₂ injection into the Shahejie Group through these designated zones. The injection was controlled using the field-monitored flow rate to ensure a realistic simulation of CO₂ migration and storage behavior. The injection configuration and perforation layout are presented in Figure 7.

4.2.3. Model Parameter Setting

Due to limited geological and petrophysical data, this study assumes interlayer heterogeneity. Porosity, permeability, and specific heat capacity vary between stratigraphic layers but are uniform within each individual layer. This simplification renders the model computationally tractable while maintaining geological realism in representing stratigraphic variability across the target groups. The hydrogeological parameters incorporated into the simulation model are summarized in Table 3, including layer-specific values for porosity, permeability, and thermal properties. Initial pressure and temperature distributions were derived from well logging data obtained at the injection site within the study area. In the numerical model, liquid- and gas-phase relative permeability and capillary pressure are calculated using the following constitutive models. Liquid-phase relative permeability is described by the van Genuchten–Mualem model, which effectively captures the nonlinear relationship between saturation and permeability in unsaturated porous media. Gas-phase relative permeability follows the Corey model, which is widely used for simulating gas transport in multiphase flow systems. Capillary pressure is computed using the van Genuchten model, allowing for a flexible representation of the capillary behavior over a broad range of saturations.

Table 3. Hydrogeologic and thermodynamic parameter settings in the model.

Argument	Value	Argument	Value
Porosity (%)	10.30~34.30	Salinity	0.03
Permeability (mD)	10.13~1833.98	Thermal conductivity coefficient (W/m °C)	2.51
Burial depth (m)	−1463.00~−1614.00	Specific Heat Capacity (J/Kg °C)	920.00
Temperature (°C)	59.51~66.89	Rock particle density (Kg/m ³)	2600.00
Pressure (MPa)	12.50	Pore compression coefficient (Pa ^{−1})	4.50×10^{-10}

4.2.4. Configuration of Simulation Scheme

In this study, the estimation of CO₂ storage potential in the research area was conducted while prioritizing reservoir safety, employing a constant pressure injection approach. This facilitated the evaluation of the influence of varying injection pressures on the total amount of CO₂ that can be stored. To reflect practical operations, multiple virtual wells were configured to inject CO₂ into two separate reservoirs simultaneously. The total simulation period was set to 30 years, comprising two phases: a 5-year CO₂ injection period representing the active phase of subsurface CO₂ emplacement, followed by 25 years of post-injection monitoring. The latter simulates long-term retention and migration of CO₂ to evaluate storage stability and assess potential leakage risks.

4.2.5. Analysis of Simulation Results

Figure 8 illustrates the evolution of group pressure in response to CO₂ injection over 5 and 30 years. It is recommended that the injection pressure not exceed 1.5 times the original formation pressure. Higher pressures may induce geomechanical stress on the caprock, increasing the risk of CO₂ leakage. Conversely, lower injection pressures may cause a decline in reservoir injectivity, ultimately reducing the achievable CO₂ storage capacity. Balancing injection pressure with storage stability is therefore essential for optimizing injection strategies while maintaining long-term storage integrity and operational safety. This study employs 1.1 times, 1.2 times, 1.3 times, and 1.5 times the group pressure as injection pressures to calculate the CO₂ injection volume.

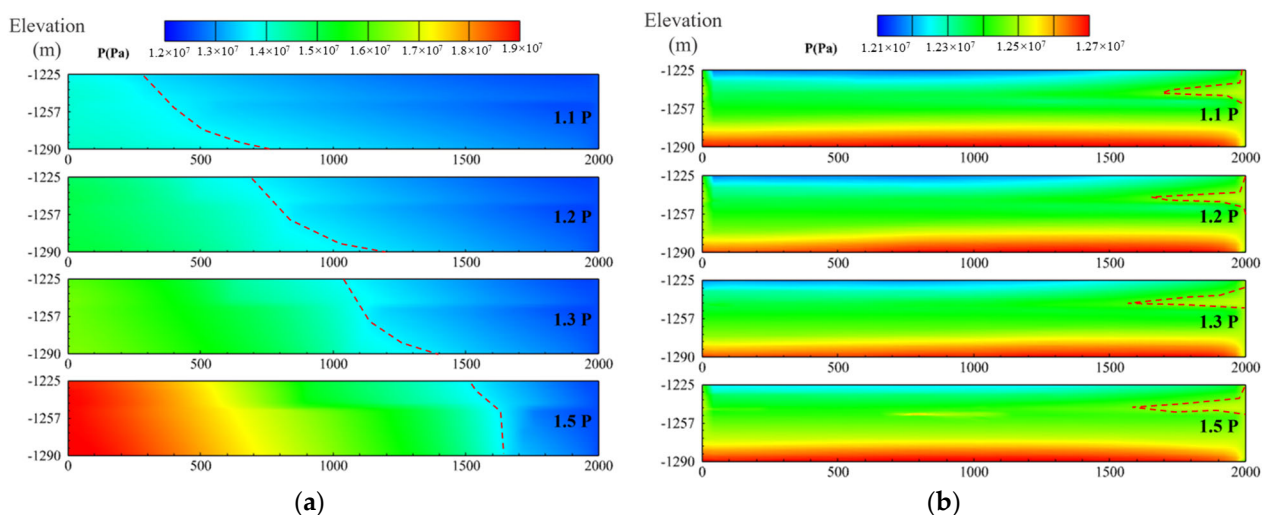


Figure 8. Group pressure distribution under different injection pressures. (a) Five years. (b) Thirty years.

As shown in Figure 8, by the fifth year of injection, the injection pressure exerts a pronounced effect on the pressure distribution within the group. When the injection pressure is set to 1.1P, 1.2P, 1.3P, and 1.5P, the corresponding influence radii in the upper

reservoir are approximately 400 m, 820 m, 1100 m, and 1650 m, respectively. Under the same conditions, the lower reservoir exhibits a broader zone of influence, attributable to its higher permeability, which facilitates more efficient pressure propagation. Notably, when the injection pressure reaches 1.5P, the group demonstrates the most pronounced pressure propagation, with a distinct pressure gradient across the reservoir. Specifically, the 0–600 m zone is defined as a high-pressure region, 600–1650 m as a medium-pressure zone, and 1650–2000 m maintains pressures close to the initial reservoir conditions. After CO₂ injection ceases at five years, the injected CO₂ gradually disperses within the reservoir and progressively dissolves into the formation water. This process reduces gas-phase accumulation and dissipates the pressure peak. By the 30th year, the reservoir reaches a quasi-equilibrium state. Nevertheless, it is evident that higher injection pressures sustain elevated stress fields over the long term.

As shown in Figure 9, the distribution of CO₂ gas-phase saturation under varying injection pressures closely follows reservoir pressure distributions. At both five and thirty years, elevated injection pressures facilitate greater horizontal migration of CO₂. In the lower reservoir, the maximum plume extents by the fifth year under injection pressures of 1.1P, 1.2P, 1.3P, and 1.5P are approximately 500 m, 750 m, 1200 m, and 1700 m, respectively. In contrast, due to the lower permeability of the upper reservoir, CO₂ migration is substantially constrained, with corresponding extents of 300 m, 490 m, 522 m, and 880 m. Following the cessation of injection, CO₂ continues to migrate outward from the injection site under pressure-driven flow. Injection pressure thus serves as a key driver of CO₂ mobility; higher pressures generate stronger hydraulic gradients, facilitating broader migration and potentially enhancing storage efficiency and containment. However, injection pressure is subject to operational and geomechanical limitations. In groups with faults or weak caprock integrity, excessive injection pressure can increase the risk of caprock breach, thereby compromising long-term storage security. By the thirtieth year, ongoing lateral migration results in maximum plume extents of approximately 1250 m (1.1P), 1720 m (1.2P), 1900 m (1.3P), and 1980 m (1.5P).

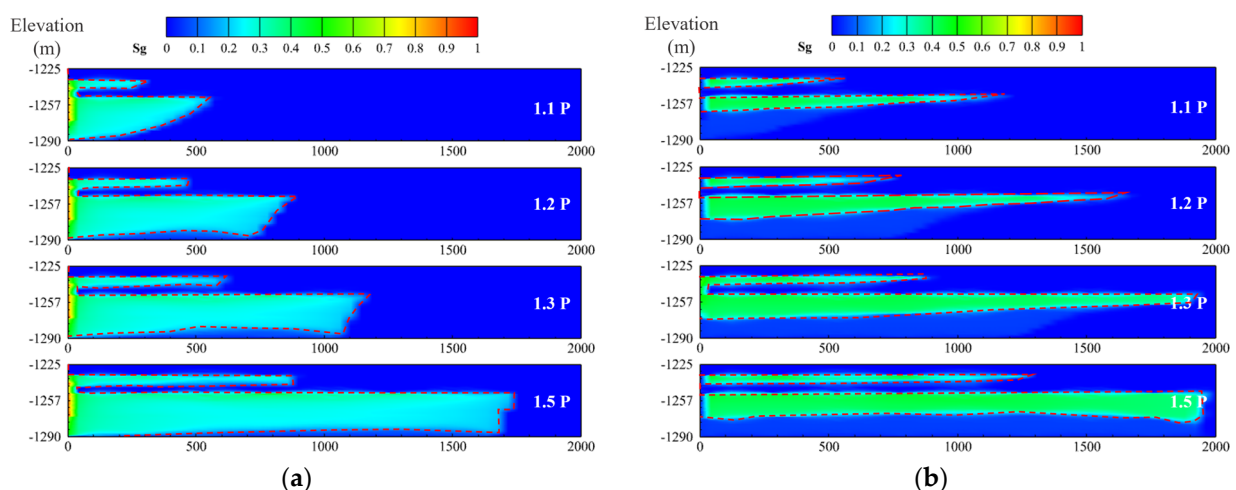


Figure 9. Distribution of CO₂ gas phase saturation varying with time under different injection pressures. (a) Five years. (b) Thirty years.

At a constant injection temperature of 55 °C, Figure 10 presents the spatial distribution of the dissolved-phase CO₂ mass fraction at five and thirty years under varying injection pressures. The distribution of dissolved CO₂ closely parallels that of gas-phase saturation. Elevated injection pressures promote plume expansion and enhance the interface between CO₂ and formation brine, thereby increasing dissolution efficiency. By year 30, the maxi-

imum lateral extent of dissolved CO₂ under injection pressures of 1.1P, 1.2P, 1.3P, and 1.5P reaches approximately 1200 m, 1650 m, 1950 m, and 2000 m, respectively. The 2000 m extent reaches the model boundary. A notable observation at 1.3P is that the CO₂ plume front in the lower reservoir reaches the lateral boundary by year thirty. This induces boundary constraints that limit further horizontal dispersion, triggering vertical migration into deeper reservoir zones. At 1.5P, this behavior becomes more pronounced, as the dissolved phase increasingly occupies the full vertical extent of the reservoir. This phenomenon suggests that in homogeneous reservoirs, CO₂ initially migrates laterally along the caprock–reservoir interface. However, upon encountering structural closures or lithological heterogeneities, the dissolution-driven convective flow transitions from lateral to vertical, promoting a more uniform three-dimensional distribution. These results highlight the complex interplay among plume dynamics, reservoir architecture, and boundary conditions. They emphasize the necessity of integrated numerical modeling to predict long-term CO₂ behavior and ensure storage integrity.

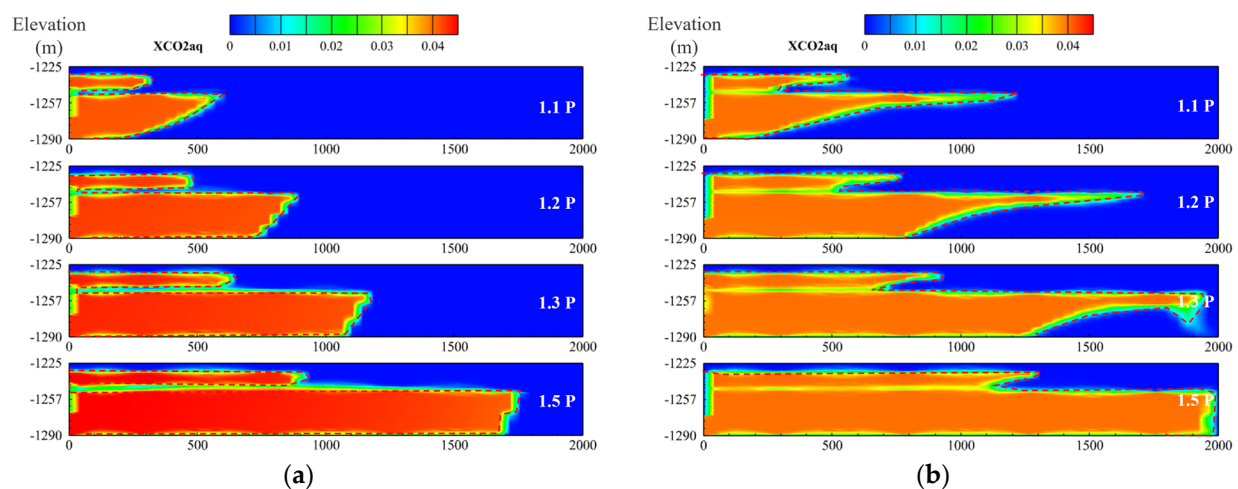


Figure 10. Mass fraction distribution of dissolved phase CO₂ under different injection pressures. (a) Five years. (b) Thirty years.

Figure 11 illustrates the significant impact of injection pressure on CO₂ storage capacity during the injection process. Given the relatively short simulation period and the exclusion of mineral storage, the total storage capacity consists of gas-phase and dissolved-phase storage, assuming no leakage occurs. By the fifth year of CO₂ injection, the total CO₂ storage in the reservoir under 1.2P, 1.3P, and 1.5P injection pressures is 1.9, 2.8, and 3.75 times greater than that under 1.1P, respectively. This indicates that higher injection pressures result in a larger total CO₂ storage capacity. The maximum storage capacity at 1.5P reaches 55.22×10^5 kg. As time progresses, gas-phase storage gradually decreases, while dissolved-phase storage increases. By year 30, dissolved-phase CO₂ storage under 1.2P, 1.3P, and 1.5P is 1.76, 2.67, and 3.32 times greater than that under 1.1P, with the maximum stable storage amounting to 43.40×10^5 kg at 1.5P. These findings underscore that higher injection pressures not only enhance CO₂ storage capacity but also accelerate the transition to dissolved-phase storage, which is more stable over time. This suggests that increasing injection pressure can optimize CO₂ sequestration while ensuring long-term storage stability. However, careful management is essential to mitigate leakage risks associated with higher pressures, particularly in reservoirs with complex geological conditions.

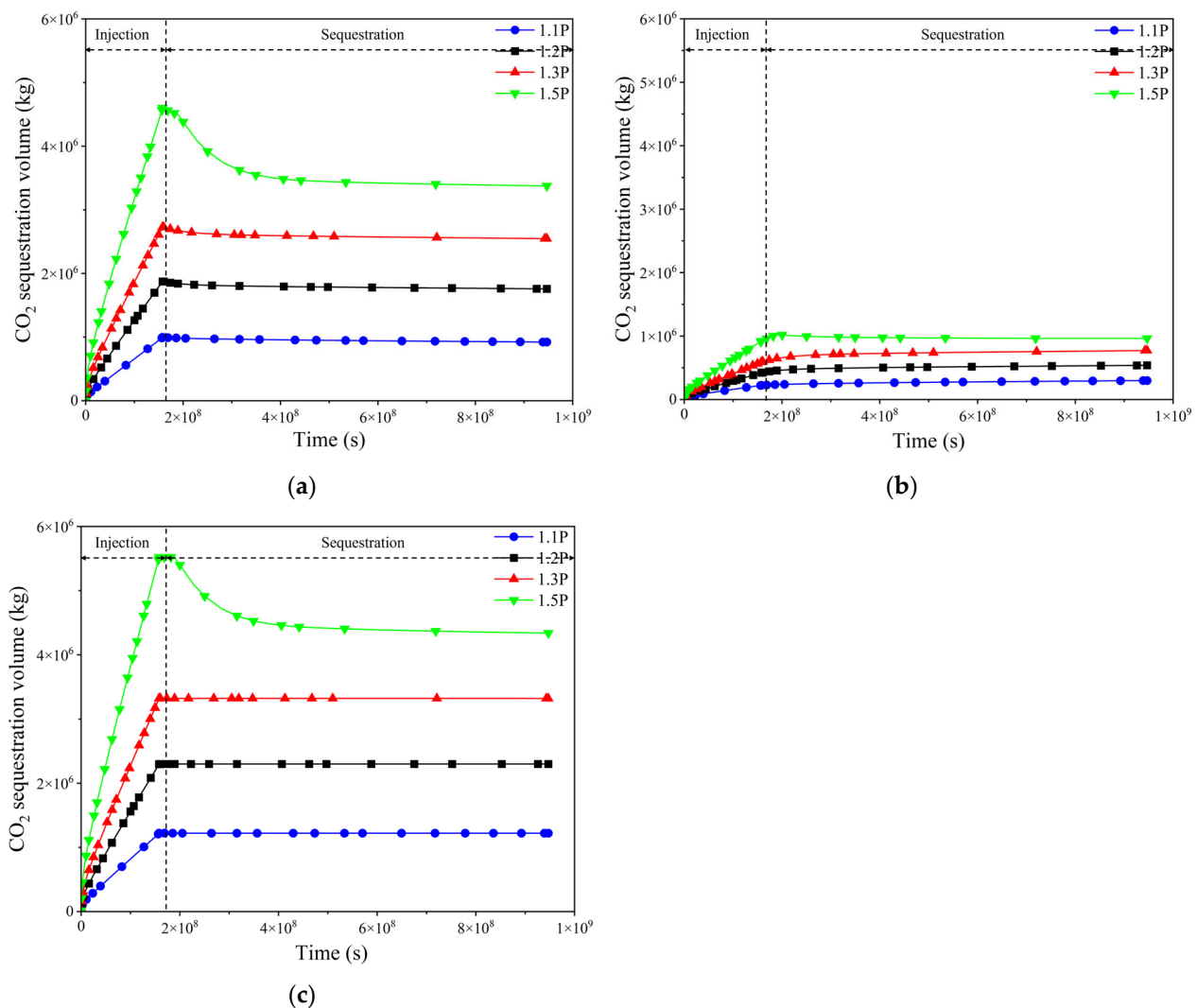


Figure 11. Variation characteristics of structural storage, dissolution storage and total storage in reservoirs. (a) Structural storage. (b) Dissolution storage. (c) Total storage.

It can be observed that under an injection pressure of 1.5P, dissolved-phase storage increases the most. This occurs because higher injection pressures increase the migration distance of the CO₂ plume, expanding the contact area with the saline water layer. As a result, dissolution efficiency improves, leading to a larger dissolved-phase storage capacity. However, the numerical simulation results show that when the injection pressure reaches 1.5 times the initial formation pressure (1.5P), the CO₂ plume breaches the model's effective storage boundary after a migration period of 2.0×10^8 seconds (approximately 6.3 years). This results in a sharp decline in total storage capacity, suggesting that, under higher injection pressures, supercritical CO₂ migrates much faster, achieving long-distance migration in a relatively short period. From a storage safety perspective, dissolved-phase CO₂ is more stable than gas-phase CO₂. At 1.5P, the lateral migration distance of CO₂ is significantly larger, and the risk of leakage through weaker strata increases substantially. This leads to a reduced dissolution period, which can undermine overall storage security. This phenomenon highlights the dual effect of injection pressure on storage safety. Within the range of 1.5 times the initial formation pressure, increasing injection pressure enhances CO₂ injection efficiency. However, when the injection pressure exceeds the critical threshold, CO₂ migrates farther laterally in a shorter time, and the dissolution period becomes shorter. In such cases, the risk of leakage through weaker strata or along high-permeability

pathways (such as faults or fractures) significantly increases. The Darcy flow rate along these pathways may exceed the sealing capacity of the cap rock, thereby increasing the probability of leakage. Therefore, it is essential to determine an appropriate injection pressure based on the characteristics of the storage group, balancing injection efficiency with safety concerns. This underscores the importance of careful management of injection pressures to optimize both sequestration efficiency and long-term storage security.

4.3. Discussion

This study systematically evaluated the CO₂ geological sequestration potential of the Dezhou Subdepression region using a multidisciplinary approach. The findings highlight the significant potential of this region for carbon sequestration, while also identifying several scientific and technical challenges that require further investigation. Geologically, the Shajie Group sandstone reservoir coupled with the Dongying Group mudstone caprock (single-layer thickness > 2.5 m; cumulative thickness > 100 m) forms an ideal storage-seal system. Reservoir heterogeneity may significantly affect the migration path of CO₂ plumes. Therefore, in practical engineering applications, optimizing well placement to align with the reservoir's physical property distribution is crucial.

At the methodological level of suitability evaluation, the AHP-FUZZY model's indicator system reflects the unique geological context of China's continental basins. This study introduces innovative parameters, such as geothermal gradient (weight: 0.0834) and degree of mineralization (weight: 0.01238). However, the model's overemphasis on structural stability (weight: 0.4761) may underestimate the long-term contribution of chemical sequestration mechanisms, such as mineral trapping, which were not considered in the simulation. This bias arises from the current lack of monitoring data from demonstration projects, and future studies will incorporate geochemical simulations to refine the evaluation system.

The numerical simulation results reveal a nonlinear relationship between injection pressure and sequestration volume, which warrants particular attention. As the injection pressure increases from 1.1P to 1.5P, the sequestration volume rises by 275%, significantly outpacing the 36% increase in pressure. This indicates that inertial forces are markedly enhanced under high-pressure conditions. However, the simulation also shows that under a pressure of 1.5P, the CO₂ plume breaches the model boundary within 6.3 years. This suggests that the high permeability of the reservoir in this region may accelerate fluid migration. Although simulation results indicate that an injection pressure of 1.5P may lead to CO₂ breakthrough at the caprock boundary, this risk can be mitigated through engineered control strategies. Based on the dynamic response of the CO₂ plume, a composite regulation strategy is recommended. This strategy primarily involves a stepwise pressure ramp-up, complemented by multi-well array scheduling. Field implementation should be supported by distributed acoustic sensing (DAS) for high-resolution pressure monitoring, enabling real-time reconstruction of the reservoir pressure field at 15 min intervals. This paradoxical phenomenon underscores the necessity of a dynamic risk assessment model that accounts for the balance between group rupture pressure, fault activation risks, and sequestration efficiency.

Although the two-dimensional radial model used in this study provides computational efficiency and compatibility with existing simulation frameworks, it inherently simplifies key aspects of subsurface heterogeneity and vertical migration dynamics. As a result, it may underestimate CO₂ migration behaviors under field conditions, particularly the preferential flow along high-permeability pathways, and may distort the spatial evolution of the pressure field. In contrast, three-dimensional modeling enables more accurate representation of anisotropic permeability, pressure interactions at the caprock–reservoir interface, and vertical heterogeneity in storage capacity. To address these limitations, future

work will focus on developing a fully coupled 3D model. This model will integrate core-scale heterogeneity reconstruction and dynamic monitoring data. Such integration will enhance the reliability and applicability of simulation outcomes for real-world geological storage projects.

5. Conclusions

The geological and numerical analysis of the Dezhou Subdepression in Shandong Province provides critical insights into CO₂ geological sequestration feasibility and operational design. The novelty of this study lies in its first-time revelation of the unique CO₂ storage mechanisms within the Dezhou Subdepression—a characteristic sandstone-shale interbedded reservoir. The optimal injection pressure was determined through the evaluation of multiple pressure scenarios (1.1P–1.5P). These findings directly support China’s million-tonne-scale CCUS demonstration project, enabling the field-scale engineering application of storage technology under complex geological conditions. Key findings are summarized as follows:

- (1) The Dezhou Subdepression demonstrates favorable reservoir caprock characteristics, including optimal burial depth (>800 m), sufficient porosity/permeability in sandstone reservoirs, and thick, low-permeability mudstone caprocks.
- (2) Numerical simulations reveal a strong correlation between injection pressure (1.1P–1.5P, where P = reservoir pressure) and storage efficiency. Total sequestered CO₂ increases by ~275% (from 1.22×10^5 kg at 1.1P to 5.52×10^6 kg at 1.5P), while lateral plume migration expands by 240%.
- (3) Optimal pressure thresholds should be maintained below 1.3P to maximize sequestration without exceeding caprock fracture gradients.
- (4) The integrated workflow (AHP-Fuzzy + Numerical simulation) provides a replicable framework for early-stage site screening in similar sedimentary basins.

These findings provide a scientific foundation for designing safe and efficient CO₂ sequestration projects in similar sedimentary basins, emphasizing the trade-offs between injection pressure optimization and long-term geological security. Future work should focus on long-term geomechanical stability assessments and field-scale pilot testing. This study still has several noteworthy limitations. (1) Although the 2D radial homogeneous model quantifies pressure sensitivity, it cannot capture fault structures or reservoir heterogeneity. Future work necessitates the development of a 3D coupled geomechanical flow model integrating stochastic heterogeneous fields and the Embedded Discrete Fracture Model (EDFM). (2) The investigated injection pressure range (1.1P–1.5P) lacks validation against caprock fracturing pressure experiments. It is imperative to conduct triaxial compression tests on caprock core samples and in situ stress measurements to define the safe operational window. (3) The numerical simulations did not incorporate a monitoring scheme. Future pilot-scale designs should optimize the deployment of distributed fiber optic sensing (DAS/DTS) and 4D seismic surveys. To advance toward pilot implementation, future efforts must prioritize geomechanical validation, high-fidelity 3D modeling, and MMV-integrated risk management—essential steps for translating theoretical storage potential into secure, large-scale carbon mitigation.

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Abbreviations

CO ₂	Carbon dioxide
AHP	Analytic Hierarchy Process
P	Original Group pressure
CCUS	Carbon capture, utilization, and storage
FUZZY	Fuzzy comprehensive evaluation method
Q ₄	Holocene Series (Quaternary)
Q ₃	Upper Pleistocene Series (Quaternary)
Q ₂	Middle Pleistocene Series (Quaternary)
Q ₁	Lower Pleistocene Series (Quaternary)
N _{2m}	Minghuazhen Group (Neogene)
N _{1g}	Guantao Group (Neogene)
E _{3d}	Dongying Group (Paleogene)
E _{2-3s}	2nd–3rd Member, Shahejie Group (Paleogene)
E _{1-2k}	Kongdian Group (Paleogene)
CI	Consistency index
CR	Consistency ratio

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