

Review article

Research Status and Prospects of Coal Mine Underground Reservoirs in China

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Abstract:

Given the acute tension between water scarcity and coal-mining activities in western China, this paper systematically reviews recent advances in the deep geological storage of mine water and the development of coal mine underground reservoirs, with the aim of promoting a shift in mine-water management from conventional end-of-pipe treatment to coordinated diversion, storage, and utilization. Drawing on a literature review, theoretical synthesis, and engineering case analyses, the study examines the development of key technical systems for coal mine underground reservoirs, including site selection, accurate storage-capacity calculation, dam-stability control, and seepage-prevention mechanisms. The review shows that storage-space characterization based on overburden-movement trajectories and dam damage-evolution models under multi-field coupling have substantially strengthened the scientific basis and reliability of engineering design for coal mine underground reservoirs. In addition, deep geological storage technology offers distinct advantages and considerable potential for the safe isolation and disposal of highly saline mine water and the control of environmental risks. The findings indicate that establishing standardized and intelligent coal mine underground-reservoir systems is a key pathway toward water-resource recycling and ecological restoration in the coal-mining regions of western China. Future research should focus on long-term dam-safety monitoring under complex multi-field coupling conditions and on coordinating coal mine underground reservoirs with pumped storage and other emerging energy-development modes.

1 Introduction

China's coal resources are characterized by a distribution pattern of abundance in the west and relative scarcity in the east, and abundance in the north and relative scarcity in the south. Energy bases such as the Ordos Basin and the Shendong coalfield in western China are central to national energy security. However, these areas are mainly located in arid and semi-arid regions, where the long-term average annual precipitation is less than 400 mm. Although the total water resources account for only 7.9% of the national total, these

regions support nearly 70% of China's coal production capacity, resulting in an inherent and severe contradiction between coal abundance and water shortage. Under conventional coal mining modes, mine inflow has long been regarded as a production hazard that must be prevented and controlled, and mine water generated during mining is usually discharged after only simple sedimentation. On the one hand, the annual discharge of coal mine water in China exceeds 4.5 billion m³, with a utilization rate below 50%, causing substantial wastage of available water resources and further aggravating regional water scarcity.

On the other hand, externally discharged mine water without advanced treatment carries coal fines, salts, and trace heavy metals, polluting surface soils and groundwater systems around mining areas. Continuous groundwater drainage during coal extraction also lowers the regional groundwater table, causing vegetation degradation, land desertification, and other ecological problems, and forming a vicious cycle of mining, drainage, water shortage, and ecological degradation.

In recent years, with the advancement of China's dual-carbon strategy and the upgrading of green-mine construction requirements, water-resource protection and coordinated utilization have become core issues in the green transformation of the coal industry. However, breaking the traditional path dependence of water abandonment during coal mining and external water transfer for water use, and achieving coordinated development of coal resources and water-resource protection, remain central challenges for both academia and engineering practice. Against this background, the research perspective has gradually shifted from single-purpose mine-water hazard control to integrated deep geological storage and coal mine underground-reservoir construction based on diversion, storage, and utilization. The core logic is to make scientific use of underground spaces formed by coal mining, such as goafs and abandoned roadways, and to store mine water that would otherwise be discharged underground, thereby converting it into a controllable and usable strategic water resource. This approach not only addresses water demand in mining areas but also reduces the environmental burden of surface water treatment, making it a key technology for water-preserved coal mining and green-mine construction.

Compared with conventional surface reservoirs and water-transfer projects, coal mine underground reservoirs have several distinctive advantages. First, they do not occupy valuable surface land resources and can avoid resettlement, land acquisition, and ecological disturbance, which is consistent with the green-development principle of not competing with residents for water or with the surface for land. Second, they can fully use underground spaces already created by coal mining, so the investment is far lower than that required for new surface reservoirs and the cost advantage is significant. Third, mine water can be naturally purified through water-rock interactions during underground storage, thereby reducing water-treatment costs. Therefore, since the concept was proposed, the technology has been widely recognized by the industry. Dozens of demonstration projects have been completed in western mining areas such as Shendong and Ningdong, producing significant economic and ecological benefits.

Although broad conceptual consensus has been reached and coal mine underground-reservoir technology has achieved preliminary engineering application, its promotion under deep and complex geological conditions still faces several bottlenecks. First, the morphology and porosity of post-mining water-storage spaces continuously evolve with mining-induced overburden movement, and the accurate characterization of dynamic storage-space features and precise calculation of effective storage capacity remain insufficient. Second, coal-pillar dams used as water-retaining structures are exposed for long periods to high hydraulic heads and highly saline mine water, but the long-

term damage-evolution mechanism under multi-field coupling remains unclear, and mature theoretical guidance for long-term dam stability control is still lacking. Third, the diffusion behavior of salts and the associated environmental risks during long-term storage of highly saline mine water have not been studied systematically, and the risk-prevention technical system remains incomplete.

This paper systematically reviews the research progress on underground coal mine reservoirs in China, aiming to provide a valuable reference for scholars engaged in this field.

2 Theoretical framework and technical system of coal mine underground reservoirs

2.1 Proposal and development of the diversion-storage-utilization theoretical framework

In response to the basic pattern of coal abundance and water scarcity in western China, Gu (2015) formally proposed the concept of groundwater protection and utilization for coal mine underground reservoirs centered on diversion, storage, and utilization. A schematic diagram of a coal mine underground reservoir is shown in Fig. 1. This concept established, for the first time, a complete technical system covering six key technologies: water-source prediction, reservoir site selection, storage-capacity design, dam construction, safe operation, and water-quality assurance. China's first group of coal mine underground-reservoir demonstration projects was successfully built in the Shendong mining area, verifying the feasibility and reliability of the technology. Gu et al. (2016) further summarized nearly 20 years of research and development, and clarified that Shenhua Group had, through long-term exploration, broken through the conceptual constraints of conventional mine-water management, overcome key technical challenges such as accurate water-source prediction and safe dam construction, formed a mature technical system, and realized large-scale engineering application.

Shi (2022) further reviewed the development of the six key technologies under the diversion-storage-use concept. Among them, water-source prediction, reservoir site selection, and storage-capacity design constitute the core prerequisites for coal mine underground-reservoir construction; dam structural design mainly addresses stability and structural connection; and safety assurance and water-quality assurance focus on the establishment of monitoring systems during operation and the clarification of water-rock purification mechanisms. The promotion of this technical system has enabled the Shendong mining area to transform from a major water consumer into a water-supply source, fundamentally changing the regional balance between water supply and demand. Based on more than 20 years of engineering practice in the Shendong mining area, Zhang et al. (2022a) systematically discussed the adaptive conditions for coal mine underground-reservoir construction and established an engineering design system centered on reservoir site selection, storage-capacity design, construction sequence of sub-reservoirs, design of coal-pillar and artificial dams, pipeline-network layout, and water-transfer systems, as shown in Fig. 2. Drawing further on the construction experience of more than

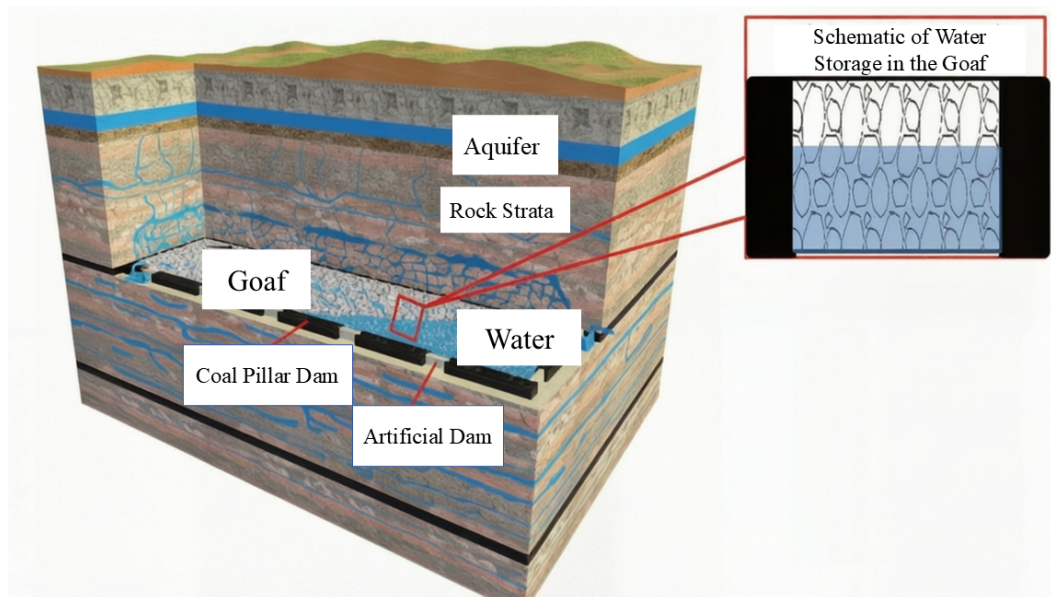


Fig. 1 Schematic diagram of a coal mine underground reservoir (Gu, 2015)

30 existing coal mine underground reservoirs, they proposed a panel-type coal mine underground-reservoir system design concept and refined core engineering technologies such as roadway layout, pipeline design, and safety monitoring, providing a directly applicable technical template for underground-reservoir design under different geological conditions.

To promote large-scale application of the technology, Li et al. (2025) conducted a systematic study from the perspective of standard-system construction. In response to the previous lack of unified standards for coal mine underground reservoirs, they explicitly proposed a theoretical framework for underground-reservoir construction and developed a technical standard system consisting of four levels: basic, comprehensive, design, construction, operation, and resource utilization standards (Fig. 3). This work filled a standardization gap in the field and provided standard support for the regulated promotion of coal mine underground-reservoir technology.

Overall, after more than a decade of development, the diversion-storage-utilization theoretical framework has evolved from an original concept into a mature technical system integrating theoretical innovation, technological research and development, engineering practice, and standard specifications. It has effectively addressed the conflict between water-resource protection and green coal development in western mining areas, and has laid a solid theoretical and technical foundation for deep geological storage and resource utilization of mine water.

2.2 Key technical systems of underground reservoirs

2.2.1 Water-source prediction and reservoir site selection

Water-source prediction and site selection are the primary prerequisites for coal mine underground-reservoir construction. Water-source prediction mainly includes two aspects: the study of groundwater migration during coal mining and the quantitative prediction of mine inflow, both of which directly determine the amount of water resources available for underground

storage. Gu (2015) proposed an integrated research method that combines multiple geophysical techniques, including four-dimensional seismic exploration, high-density electrical methods, and geological radar, with field hydrogeological observations and physical-numerical simulation. This method successfully clarified the migration patterns of Quaternary pore water and bedrock fissure water under modern coal-mining conditions in western mining areas, providing a methodological basis for water-source prediction and site selection. Gu et al. (2016) further emphasized that water-source prediction and reservoir site selection are the first steps among the six core technologies. Site selection for coal mine underground reservoirs must move beyond the traditional concept of blocking groundwater and should scientifically select storage locations based on groundwater migration patterns in mining areas, so as to maximize the use of natural conditions and reduce engineering investment (Gu et al., 2016).

Shi (2022) identified water-source prediction and reservoir site selection as the core preliminary tasks for coal mine underground-reservoir construction. The key issues include detailed investigation of engineering-geological and hydrogeological conditions, characterization of groundwater migration after coal extraction, and quantification of void characteristics and bulking behavior of caved rocks in goafs. Only after these basic tasks are completed can the scientific basis of subsequent engineering design be ensured. Zhang et al. (2023b) and Guo et al. (2023) proposed an entropy-weight-based geological site-selection method that considers indicators such as coal-seam thickness, sandstone ratio, and aquiclude thickness. Corresponding hydrochemical constraints were also proposed for site selection involving high-fluorine and high-hardness water sources. When constructing the standard system for coal mine underground reservoirs, Li et al. specifically incorporated water-source prediction and reservoir site selection into the categories of basic standards and design standards, clarifying standardized procedures and technical requirements and further

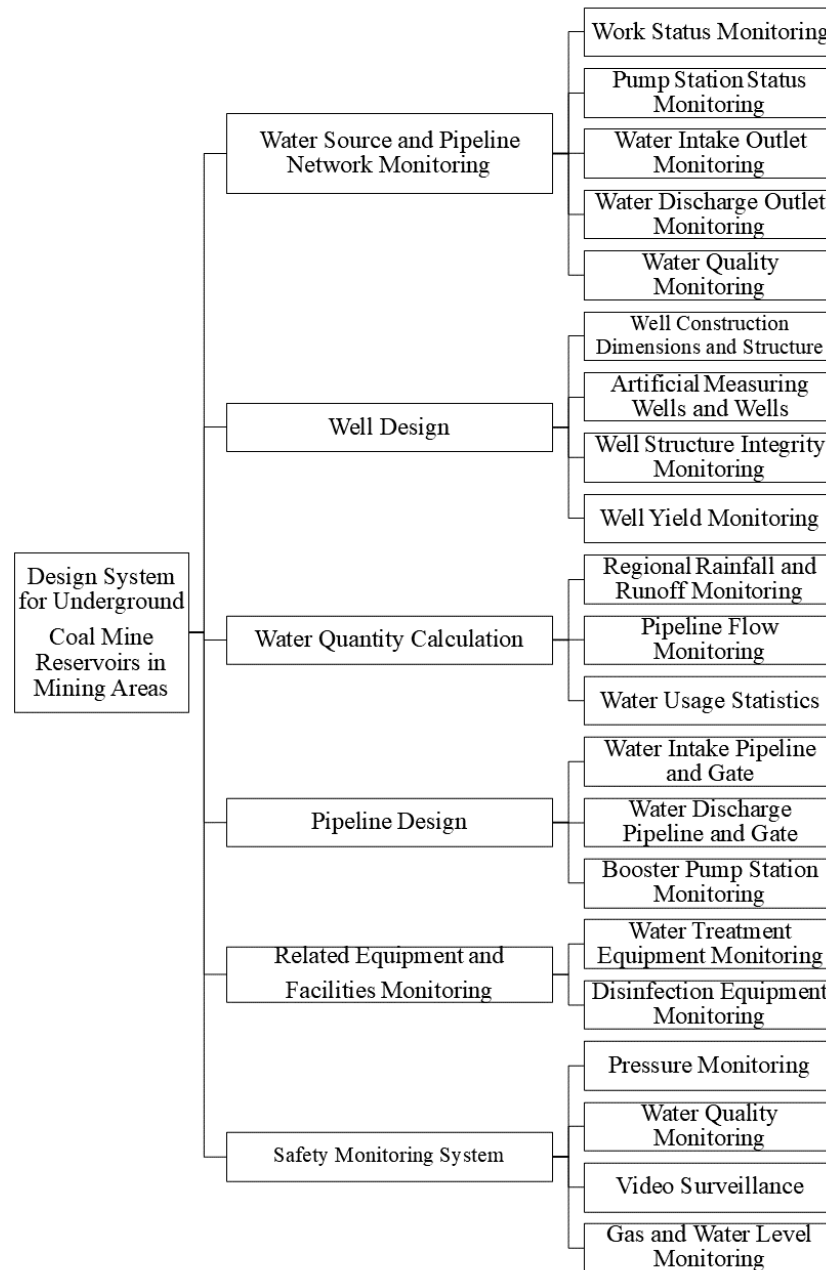


Fig. 2 Design system of a panel-type coal mine underground reservoir (Zhang et al., 2022a)

regulating technical application in this stage (Li et al., 2025).

At present, water-source prediction and reservoir site-selection technology has developed from early qualitative theoretical exploration into a mature technical system integrating multi-geophysical detection, numerical-simulation inversion, and field verification, providing solid support for safe and efficient coal mine underground-reservoir construction under different geological conditions.

2.2.2 Storage-capacity design and dam construction

The core task of storage-capacity design is the accurate quantification of effective underground water-storage space, which forms the key basis for ensuring that underground reservoirs meet regional water demand. For western mining areas where

near-horizontal coal seams are widely developed and accurate calculation methods for effective storage space had long been lacking, Pang et al. (2019) proposed calculating the volume difference before and after rock caving by using the vertical displacement trajectory equation of overlying strata, thereby determining the effective water-storage space in the caving zone and block-hinged zone and deriving the corresponding theoretical formulas. Field pumping and drainage tests at the Daliuta Coal Mine verified that the calculation accuracy meets engineering design requirements. Ju et al. (2017) clarified that the total water-storage capacity of a coal mine underground reservoir consists of two parts: the free voids among broken rocks in the caving zone and the bed-separation fissures in strata

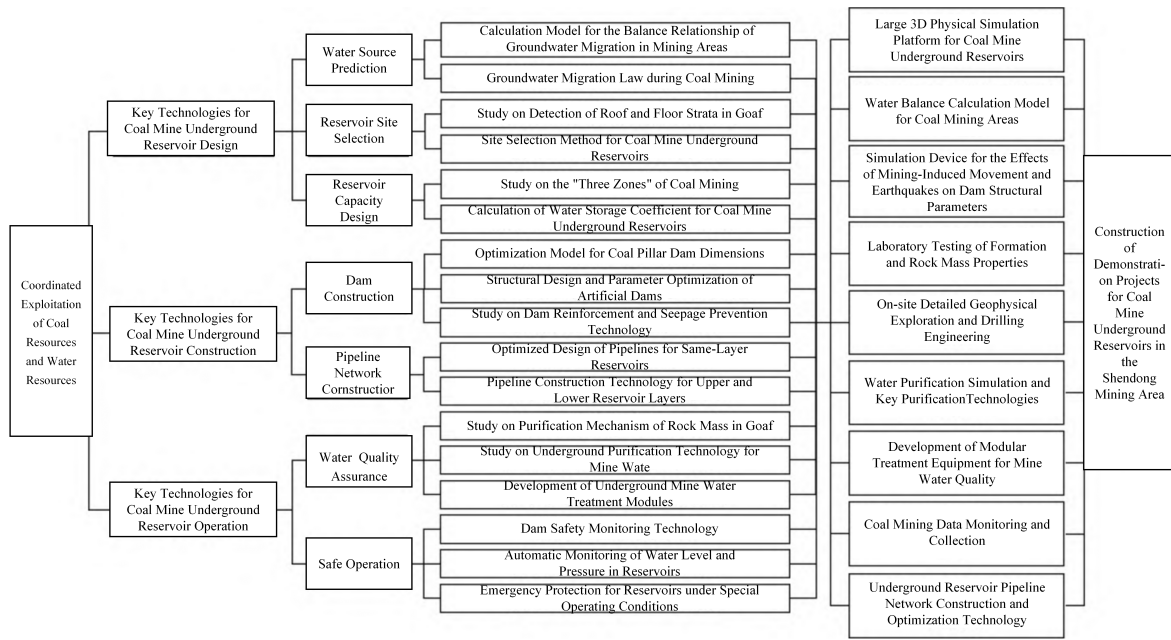


Fig. 3 Theoretical and technical framework of coal mine underground reservoirs (Li et al., 2025)

of the fractured zone. Based on this understanding, they established methods for determining limiting and reasonable storage capacity considering the effect of coal-seam dip, providing a theoretical basis for storage-capacity calculation in coal seams with different dips. To address the low efficiency and poor accuracy of conventional manual calculations, Jiang et al. (2020) developed a rapid storage-capacity calculation platform based on GIS and CAD integration. By constructing water-storage volume elements with a triangulated irregular network model and matching corresponding storage coefficients, the platform realized rapid and accurate storage-capacity calculation, with measured errors controlled within 3%, substantially improving the efficiency and accuracy of storage-capacity design.

Dam construction is central to the safe operation of underground reservoirs. Water-retaining dams in coal mine underground reservoirs comprise artificial dams and coal-pillar dams. For artificial dams, Bai et al. (2017) analyzed the stability of an artificial dam under different water heads based on the Drucker-Prager strength criterion, using the Lijiahao Coal Mine underground reservoir as a case study. The results indicated that the midpoint of the bottom edge on the outer surface was the most vulnerable location for instability, and the ultimate water head of the artificial dam in this project was 17.8 m, consistent with field measurements. Chen (2015) investigated the seepage-field characteristics of different types of water-retaining dams through finite-element numerical simulation and confirmed that installing an anti-seepage curtain can effectively block upstream inflow, markedly reduce dam seepage, and improve dam stability. Fan et al. (2020a) used FLAC3D numerical simulation to examine the effects of different confining-pressure conditions on artificial-dam stability, and found that uniform confining pressure of relatively low intensity can effectively constrain dam deformation and enhance stability, whereas high confining pressure or non-uniform confining pressure

accelerates dam failure. This conclusion informs artificial-dam site selection and design.

For coal-pillar dams, Wu used similarity-model tests to investigate the optimal layout of coal-pillar dams in distributed coal mine underground reservoirs and proposed that an aligned arrangement in the direction perpendicular to the coal-seam plane provides the best stability (Wu, 2018). Wang (2022) investigated the damage mechanism of coal-pillar dams under long-term immersion in high-concentration brine, revealing that diffusion of salt ions into coal and rock gradually deteriorates their mechanical properties and confirming the adverse effect of long-term immersion on coal-pillar dam stability. Xu et al. (2025a) further developed a comprehensive coal-pillar dam stability evaluation model based on analytic hierarchy process and fuzzy theory, and quantitatively evaluated coal-pillar dams at the Shigetai Coal Mine in the Shendong mining area, providing a practical method for stability assessment in engineering practice.

Overall, existing research has evolved from early single theoretical derivation into a multidimensional technical system combining theoretical analysis, numerical simulation, field testing, and intelligent calculation, providing solid theoretical support and engineering guidance for the safe and efficient construction of coal mine underground reservoirs.

2.2.3 Safe operation and water-quality assurance technologies

Safe operation and water-quality assurance are essential requirements for the long-term operation of coal mine underground reservoirs. The objective of this technical direction is to ensure long-term dam stability, prevent dam-break seepage and leakage, and ensure that stored mine water meets utilization requirements by establishing integrated monitoring and emergency-response systems in combination with water-rock self-purification. Regarding safe operation, Cao et al. applied

systems-engineering theory to analyze key factors affecting underground-reservoir safety and constructed an emergency assurance technical system and supporting monitoring system covering dam-break prevention, seepage prevention, and siltation prevention (Cao et al., 2014). Application at the Daliuta Coal Mine in the Shendong mining area showed that the system can maintain operational safety through real-time monitoring and automatic dispatching. Chen systematically examined the effects of anti-seepage curtains of different lengths on seepage fields for seepage-induced failure of water-retaining dams and confirmed that curtain grouting can effectively reduce seepage, providing a basis for dam safety evaluation (Chen, 2015). Gu noted that coal mine underground reservoirs designed under the diversion-storage-use concept can achieve long-term, low-cost, safe, and stable operation (Gu, 2015). Using the Daliuta Coal Mine as a case study, Chen et al. introduced the engineering practice of constructing a three-dimensional network-like underground-reservoir system using the diversion-storage-use technical system (Chen et al., 2016). The project enabled efficient mine-water reuse and substantially reduced mine-water hazards at the site. Huang et al. simulated dynamic changes in groundwater level during working-face retreat using independently developed numerical software, characterized the evolution of seepage fields under different retreat conditions, and provided theoretical support for predicting groundwater-flow characteristics and ensuring safe operation (Huang et al., 2022).

For water-quality assurance, Fang et al. (2022) investigated the mechanism of water-rock interactions in underground reservoirs and found that minerals such as chlorite in roof-caved rocks have significant adsorption and ion-exchange effects on metal ions in mine water. These results help explain how goaf rock masses purify mine water and provide a basis for using natural processes to purify mine water. Shi (2022) systematically reviewed progress in this direction and emphasized that 24-h real-time automatic monitoring of dam stress-strain and reservoir water quality is an essential prerequisite for safe operation. Wang (2022) focused on the time-dependent stability of coal-pillar dams under long-term brine immersion and analyzed deterioration laws through field investigation and numerical simulation, supporting long-term safe operation. Du et al. (2025) further proposed a deep geological storage technical system for mine water oriented toward China's carbon-neutrality goals, discussed the feasibility of isolating highly saline mine water from the biosphere by using deep independent geological spaces, and broadened the options for safe disposal of highly saline mine water.

Overall, research has progressed from isolated safety monitoring into a complete technical system covering seepage-field control, water-rock self-purification mechanisms, time-dependent dam stability analysis, and deep storage. This progress has significantly improved the operational safety and water-quality assurance capacity of coal mine underground reservoirs. Nevertheless, the dynamic evolution mechanism under long-term complex multi-field coupling conditions still requires further investigation. Table 1 compares the principal monitoring methods used for coal mine underground reservoirs.

2.2.4 Standard system for coal mine underground reservoirs

Gu et al. (2016) pointed out that coal mine underground-reservoir technology had matured in the Shendong mining area and urgently needed to be promoted to other western mining areas. Such promotion must rely on a standardized and normalized technical system, indirectly revealing the industry's urgent demand for standards. Before this, coal mine underground reservoirs had long lacked unified technical standards, and obvious gaps existed in core technical standards for basic and comprehensive fields. A large number of early research and development achievements had not been transformed into normative technical documents, restricting large-scale promotion. In response to this industry pain point, Li et al. (2025) conducted a systematic industry survey and established China's first technical standard system for coal mine underground reservoirs based on the principles of clear objectives, comprehensive completeness, clear hierarchy, scientific practicality, and openness for expansion. As shown in Fig. 4, the technical standard system comprises four levels and covers six categories: basic, comprehensive, design, construction, operation, and resource-utilization standards. It achieves full coverage of core technologies across the entire underground-reservoir process and specifies the standards that should be prioritized in the short and medium term, thereby indicating the pathway for standard compilation.

Overall, coal mine underground-reservoir technology has progressed from the early stage of engineering demonstration into a new stage of standardized system construction. Existing research has filled the standardization gap in this field and provides important institutional guarantees and technical support for the large-scale promotion of the technology and the construction of green mines

3 Storage-capacity calculation for coal mine underground reservoirs

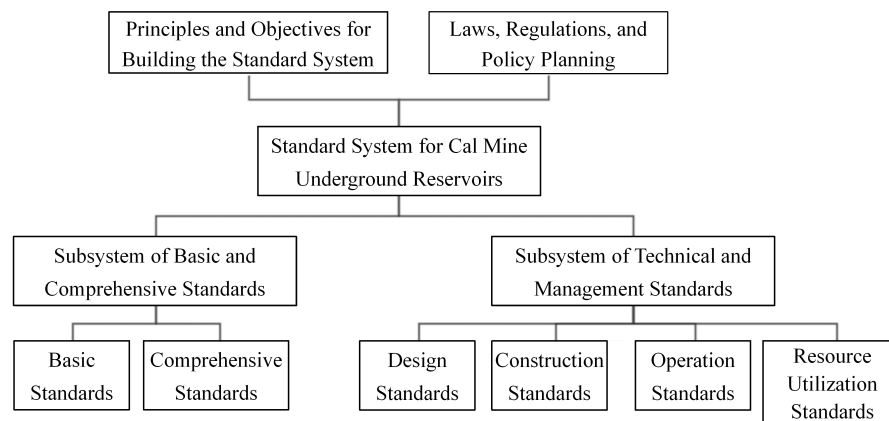
3.1 Formation mechanism and zoning characteristics of water-storage space

After coal mining, the overlying strata undergo caving, fracturing, and deformation, forming a mining-induced fracture network. The effective water-storage space of a coal mine underground reservoir is composed of voids generated by mining and can be divided into two parts: free voids among broken rocks in the caving zone and bed-separation fissures between fractured strata in the separation zone. Existing studies usually combine theoretical derivation with numerical simulation to quantify the total volume of these two types of voids and thereby determine the effective water-storage space.

Ju et al. (2017) combined theoretical analysis, laboratory simulation, and field measurement to establish a quasi-parabolic geometric model for the overburden caving zone. They derived a formula for calculating the void volume of the caving-zone rock mass considering the influence of coal-seam dip, and further combined this with the O-ring theory of mining-induced overburden fracture distribution to obtain methods for determining the void volume at the bottom interface of key strata and between adjacent key strata. A complete

Tab. 1 Comparison of monitoring methods for coal mine underground reservoirs

Monitoring category	Main indicators or data	Primary purpose	Application characteristics and limitations
Dam structural monitoring	Stress, strain, displacement, and deformation	Identify damage development and instability precursors	Directly reflects structural response; interpretation requires baseline values and long-term thresholds
Water-level and seepage monitoring	Reservoir level, groundwater level, seepage discharge, and seepage pressure	Detect abnormal leakage and support water-volume regulation	Suitable for continuous operation; sensor locations may not capture all fracture-controlled pathways
Water-quality monitoring	pH, electrical conductivity, hardness, COD, ammonia nitrogen, and metal ions	Track water-rock interaction and determine suitability for reuse	Requires regular sampling and quality control; indicators vary with water source and storage duration
Integrated monitoring and automatic dispatch	Combined water-level, dam-condition, water-quality, and operating data	Provide early warning and coordinate reservoir-group operation	Improves system-level management but requires data integration and site-specific warning rules
Simulation-assisted assessment	Predicted groundwater levels, seepage fields, and concentration fields	Extend interpretation beyond instrumented locations and evaluate operating scenarios	Provides predictive support rather than direct measurement and must be calibrated against field data

**Fig. 4** Technical standard system for coal mine underground reservoirs (Li et al., 2025)

mathematical expression for the storage capacity of coal mine underground reservoirs was thus established, providing a fundamental theoretical framework for storage-capacity calculation. Pang et al. (2019), to address the difficulty of accurately determining effective water-storage space in near-horizontal coal seams, proposed a method that calculates the volume difference before and after rock caving by using the vertical displacement trajectory equations of overlying boundary strata. Based on structural mechanics and fracture mechanics, they derived vertical displacement trajectory equations for three typical overburden structures, namely masonry beams, stepped rock beams, and complete caving, and obtained theoretical expressions for the effective water-storage space of the caving zone and block-hinged zone in near-horizontal coal seams. The method was verified by both UDEC numerical simulation and field pumping-drainage tests, confirming the reliability of the estimates. Wang et al. (2019a), based on thin-plate deflection theory and the Winkler elastic foundation plate principle, derived a differential

equation for the subsidence trajectory function of key strata and established a mathematical model for the spatial distribution of rock stress in shallow-buried goafs. The study revealed U-shaped subsidence characteristics in fractured-zone strata and inverted U-shaped stress variation in caving-zone rock masses, providing a basis for storage-capacity design under shallow-buried coal-seam conditions. Hu et al. (2024), using the Lingxin Coal Mine in Ningxia as an engineering case, determined the morphological characteristics of the caving zone and water-conducting fracture zone by 3D-DDA numerical simulation. They then calculated average porosities of approximately 0.201 for the caving zone and 0.086 for the water-conducting fracture zone using an image-comparison method, and estimated the total reservoir capacity based on porosity. This work improved the characterization of water-storage characteristics in damaged surrounding rock and provided a new method for storage-capacity calculation in complex geological settings.

Overall, research has progressed from individual theoretic-

cal formulas into a multi-method integrated technical system combining numerical simulation and field measurement. This system can quantify the void volumes of the caving and separation zones with relatively high accuracy and provides solid support for storage-capacity design and safe operation of coal mine underground reservoirs.

3.2 Evolution of storage-capacity calculation methods

3.2.1 Determination of limiting and reasonable storage capacity based on theoretical formulas

Storage-capacity calculation requires quantification of two core parameters: the maximum amount of water that can be stored in the caving and fractured zones of a goaf, namely the limiting storage capacity, and the optimal storage scale that balances engineering safety and economic benefit, namely the reasonable storage capacity. Together, these parameters determine the design scale of an underground reservoir. Ju et al. (2017), in response to the demand for water-preserved coal mining in western mining areas, first clarified the composition of storage capacity, established a calculation formula considering coal-seam dip, and developed a method for determining limiting and reasonable storage capacity under water-level constraints. This method has successfully guided the design and construction of multiple projects. Pang et al. (2019) further refined the calculation method for water-storage space in near-horizontal coal seams, improved calculation accuracy through the vertical displacement trajectory method, and revealed the spatiotemporal evolution of water-storage space during mining, further enhancing calculation reliability. Traditional estimation methods often ignore compaction deformation of broken rock. Qin et al. (2023) considered the effects of overburden stress, water-immersion softening, and gangue particle size, and established a more accurate storage-coefficient model. The results showed that the storage coefficient decreases exponentially with increasing stress. Using the Lingxin Coal Mine as a case study, Hu et al. (2024) accurately calculated the porosity of different zones using 3D-DDA numerical simulation and obtained the total storage capacity by combining it with the storage-coefficient method, providing a practical calculation pathway and technical guidance for resource reuse of goafs. Overall, methods in this direction have evolved from early single theoretical models into integrated calculation methods combining theoretical derivation, numerical simulation, and field verification. This evolution has significantly improved the accuracy and scientific basis of storage-capacity calculation and provides a sound theoretical basis for safe design and operation of underground reservoirs.

3.2.2 Rapid and accurate storage-capacity calculation platform based on GIS and CAD

Conventional storage-capacity calculation relies on manual computation, which is inefficient and inaccurate and cannot meet the needs of large-scale engineering design. To address this problem, Jiang et al. (2020) developed a rapid and accurate storage-capacity calculation method for coal mine underground reservoirs based on GIS and CAD integration. Through secondary development, the method reads CAD floor contour data,

uses the triangulated irregular network model in GIS to construct water-storage volume elements, assigns corresponding storage coefficients to different lithologic regions, and finally develops a web-based storage-capacity calculation platform using C# and the .NET platform. Engineering measurements show that the calculation error can be controlled within 3%, while the computational efficiency is several times higher than that of conventional manual methods, substantially improving the efficiency and accuracy of storage-capacity calculation.

From the establishment of theoretical formulas to the verification of numerical-simulation results and the development of GIS-CAD integrated calculation platforms, storage-capacity calculation technology for coal mine underground reservoirs has completed the transition from manual estimation to digital and automated precision calculation. It can meet the design requirements of projects of different scales and provides robust technical support for scientific design and safe operation of underground reservoirs.

The available methods are complementary rather than interchangeable. Closed-form theoretical formulas are transparent, inexpensive, and useful for preliminary design, but their homogeneous-strata and idealized-caving assumptions can bias results when lithology and compaction vary spatially. Numerical methods such as UDEC, 3D-DDA, and coupled seepage-mechanical models represent discontinuities and stress-dependent porosity more realistically, yet their predictions are sensitive to constitutive parameters, boundary conditions, and calibration data. GIS-CAD platforms rapidly integrate mine geometry and are well suited to reservoir-group screening, but they do not remove uncertainty in storage coefficients and generally describe a static geometry. Pumping-drainage or tracer tests provide the strongest site-specific validation, although they are costly and usually become available only after mining.

3.3 Storage-capacity assessment and joint dispatching of distributed underground reservoirs

3.3.1 Multi-reservoir connectivity mechanisms and joint water dispatching strategies

For large mining areas, the storage capacity of an underground reservoir formed by a single goaf is usually limited and cannot meet large-scale storage and water-use requirements. Distributed underground-reservoir technology has therefore been developed. In this approach, multiple underground reservoirs formed by adjacent goafs are connected through roadways and pipelines to create an interconnected reservoir group, and a pipe-network system enables flexible spatial allocation and joint dispatching of water. This solves the problems of insufficient single-reservoir capacity and difficult inflow safety control. A schematic diagram of a distributed coal mine underground reservoir is shown in Fig. 5. Liu et al. (2019), focusing on the disturbed fracture field and mine-water storage safety caused by large-scale coal mining, proposed the technical idea of constructing multiple underground reservoirs and connecting them by pipelines to form a distributed underground reservoir. They established a groundwater numerical simula-

tion model to predict mine inflow and optimized dispatching based on the relationship between water supply and demand in the mining area together with surface water resources. The results confirmed that joint dispatching among reservoirs can effectively control the water volume stored in underground reservoirs that threaten production panels and prevent water hazards. Based on years of engineering practice in the Shendong mining area, Zhang et al. (2022a) further constructed a panel-type coal mine underground-reservoir system design framework and described in detail the construction sequence of sub-reservoirs, pipeline-network layout, water-transfer systems, and other core technologies. They showed that systematic pipeline design and dispatching strategies can enable efficient use of water across the mining area, and emphasized the key roles of pipe-network and roadway layout, water-transfer systems, and safety monitoring systems in multi-reservoir connectivity and joint dispatching, providing a complete design basis for promoting distributed underground reservoirs.

Overall, multi-reservoir connectivity mechanisms and coordinated water-dispatching strategies are core technologies for ensuring safe operation of coal mine underground reservoirs and efficient water-resource utilization in large mining areas. Through numerical simulation and systematic engineering design, these technologies have enabled a transition from single water storage to dynamic regulation, effectively balancing mine-water storage safety with production and domestic water demand in mining areas.

3.3.2 Dynamic storage-capacity control based on seepage-field evolution

Dynamic capacity control requires operators to monitor and analyze the spatiotemporal evolution of the seepage field inside coal mine underground reservoirs, and dynamically adjust water-storage strategies and capacity-control parameters. This balances water use efficiency with engineering safety and stability, and prevents dam instability or seepage pollution caused by excessive water levels. Chen (2015) simulated the seepage field of an underground reservoir containing coal-seam structures and mining-damaged zones using the finite-element method, compared seepage characteristics under anti-seepage curtains of different lengths, and confirmed that anti-seepage curtains can effectively block upstream water flow and reduce dam seepage, providing a basis for anti-seepage design in capacity control. Huang et al. (2022) simulated dynamic changes in groundwater level during working-face retreat using independently developed numerical software, revealed seepage-field evolution under different retreat conditions, and provided theoretical support for predicting groundwater-flow characteristics and ensuring underground-reservoir safety. Wu et al. (2021) used solid-liquid coupled similarity-model tests and multi-field coupled numerical simulation to analyze the seepage and diffusion process of highly saline mine water in mining-induced fracture networks. They clarified the diffusion paths of the concentration field over time and its potential influence on adjacent aquifers, providing key data for setting safe storage-capacity thresholds during highly saline mine-water storage. Yu (2024) further developed a mining-induced coal damage-permeability model considering triaxial stress and

a zoned fluid-solid coupling model, characterized the water-absorption characteristics and seepage evolution laws of coal and rock in complex immersion environments, and proposed a bearing-seepage zoning method for coal-pillar dams, further refining the mechanism by which seepage fields influence storage-capacity stability. Overall, research has advanced from individual seepage-field simulations to dynamic evolution analysis under multi-field coupling. It has confirmed that seepage-field characteristics are the core factor determining the safe upper limit of underground-reservoir capacity. In the future, real-time monitoring data should be integrated to establish dynamic storage-capacity regulation models based on seepage evolution, thereby enabling efficient and safe utilization of mine-water resources.

4 Dam stability and seepage prevention in underground reservoirs

4.1 Stability analysis and failure characteristics of artificial dams

Artificial dams are water-retaining structures that connect coal pillars and rock walls in coal mine underground reservoirs. They are usually cast with concrete and mainly bear the coupled effects of overburden pressure and lateral water pressure; their stability directly determines underground-reservoir safety. Using the Lijiahao Coal Mine underground reservoir as a case study, Bai et al. (2017) conducted numerical analysis of artificial-dam stability based on the Drucker-Prager criterion and investigated dam stress distribution under different water heads. The results indicated that, under hydrostatic pressure, DP stress peaks tend to occur at the midpoint of the inner surface and at the midpoints of the four edges of the outer surface, with the midpoint of the bottom edge on the outer surface being the most vulnerable to instability. The ultimate bearing water head of the artificial dam was calculated as 17.8 m, and the result was verified by COMSOL numerical simulation and field measurements. Fan et al. (2020a) used FLAC3D to systematically analyze the stress environment at artificial-dam construction locations, pointing out that a confining-pressure environment forms around the dam after impoundment. Moderate uniform or non-uniform confining pressure can improve artificial-dam stability, but high uniform confining pressure or significantly non-uniform confining pressure can instead promote dam failure, and the failure characteristics differ markedly from those under no confining pressure. Although Wang (2022) focused on the damage mechanism of coal-pillar dams under brine immersion, the study based on the Lingxin Coal Mine in the Ningdong mining area also found that the physical and mechanical properties of coal and rock deteriorate under long-term water immersion. This indirectly supports the conclusion that confining pressure and water quality jointly affect the time-dependent stability of dams under coupled stress and hydrochemical conditions. Kong et al. (2021, 2024) established a mechanical model based on elastic thin-plate theory and derived a formula for calculating the ultimate water head of artificial dams. The groove region was confirmed to be the weakest part of the dam and the most prone to seepage and failure. Studies on seismic response found that water pressure mainly controls the peak total displacement,

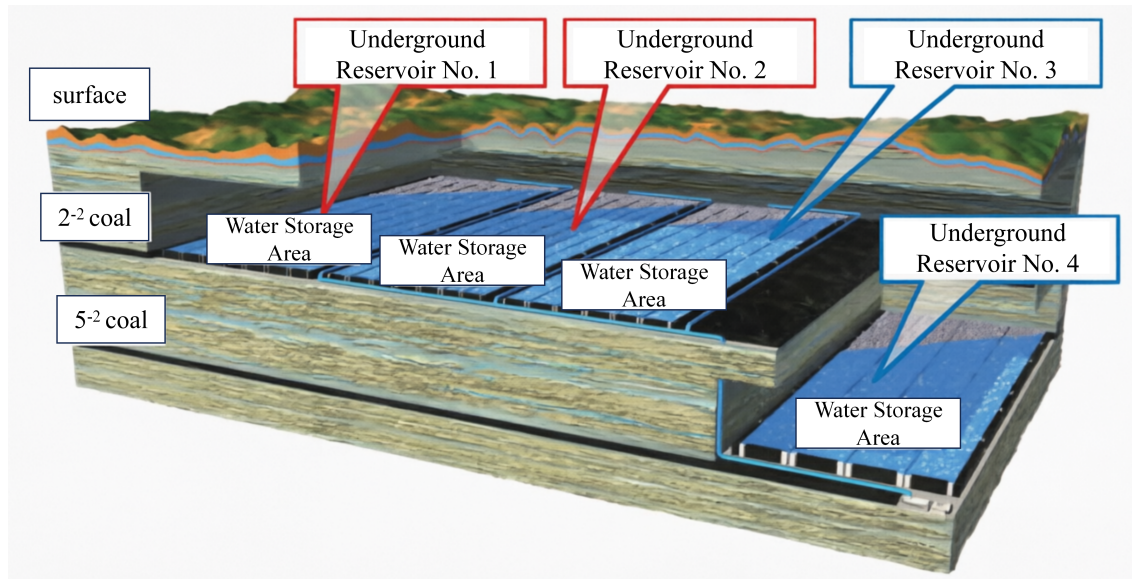


Fig. 5 Schematic diagram of a distributed coal mine underground reservoir (Li et al., 2025)

whereas peak ground acceleration mainly controls the dynamic increment. Among different dam types, an arch-equivalent dam shows the best displacement response (Xu et al., 2026). To improve the crack resistance of artificial-dam concrete under hydro-mechanical coupling, studies have shown that adding nanomaterials, such as 3% nano- Al_2O_3 , can significantly enhance the strength and bearing capacity of saturated concrete and suppress crack propagation (Hao et al., 2022). Overall, the evidence shows that the influence of confining pressure on artificial-dam stability is strongly nonlinear. Moderate confining pressure can provide constraint and enhance stability, whereas excessive or unevenly distributed confining pressure may induce dam failure. Future research should further combine multi-field coupling theory to accurately quantify artificial-dam safety thresholds under different geological stress conditions and provide a more precise basis for design.

4.2 Damage mechanisms and time-dependent stability of coal-pillar dams

Coal-pillar dams use reserved coal pillars as water-retaining structures and are the most widely applied dam type in coal mine underground reservoirs. During long-term operation, highly saline mine water causes physicochemical damage to coal and rock, ultimately weakening their macroscopic mechanical properties and affecting dam stability. Using the Lingxin Coal Mine in Ningdong as a case study, Wang (2022) investigated the effects of immersion duration, salt-solution pH, and concentration on the mechanical properties of coal and rock through field investigation, laboratory immersion tests, and acoustic-emission monitoring. The results indicated that the peak strength and elastic modulus of coal and rock decrease logarithmically with immersion time and linearly with increasing salt-solution concentration. Neutral salt solutions have the weakest deterioration effect, whereas stronger acidity or alkalinity aggravates deterioration. Using the Chahasu Coal Mine in the Shendong mining area as a case study, Yu (2024) developed intelligent non-destructive cyclic pressurized water-immersion

test equipment and further characterized the water-absorption characteristics and damage mechanisms of coal and rock in complex immersion environments. The study indicated that, under cyclic pressurized immersion, the saturated water content of coal samples has an exponential relationship with the number of immersions and immersion pressure. With increasing immersion cycles, peak strength, elastic modulus, and various stress thresholds decrease exponentially, residual strength decreases approximately linearly, and the failure mode gradually changes from mixed tensile-shear failure to tensile failure. Mining in adjacent working faces significantly expands the plastic zone of coal-pillar dams and intensifies stress concentration. Long-term water immersion softens coal and rock masses, reduces their strength, and changes the failure mode from brittle to ductile (Yao et al., 2021; Wang et al., 2023). For coal-pillar width design, Fan et al. proposed a three-zone distribution theory consisting of a seepage zone, an elastic compacted water-resisting zone, and a plastic zone, and noted that reasonable coal-pillar width should be determined through numerical simulation according to lateral water pressure and overburden stress (Fan et al., 2020a).

To quantitatively evaluate coal-pillar dam stability, Yu (2024) investigated the water-absorption characteristics and multi-scale structural damage evolution of coal and rock under complex immersion conditions. An ideal elastic model and a damage-permeability model for mining-induced coal considering triaxial stress were established, a bearing-seepage zoning method for coal-pillar dams was proposed, and the corresponding zoned fluid-solid coupling model was developed. Xu et al. (2025a) further constructed a comprehensive evaluation model for coal-pillar dam stability based on analytic hierarchy process and fuzzy theory. The model includes four criterion layers, namely dam parameters, water-immersion effects, coal-seam occurrence conditions, and mining influence, and provides specific grading standards and membership functions that can be directly used for stability evaluation in engineering

practice. Overall, existing research has advanced from early single seepage analysis to the clarification of complex damage-seepage-stress multi-field coupling mechanisms, and has gradually established a complete theoretical system from microscopic damage mechanisms to macroscopic stability evaluation. This provides a solid scientific basis for the long-term safe operation of coal mine underground reservoirs.

4.3 Seepage-prevention forms and optimization of seepage-control effects

4.3.1 Barrier effect and optimized layout of anti-seepage curtains on seepage fields

Installing anti-seepage curtains is a core technical measure for dam seepage prevention. Its principle is to form a low-permeability water-blocking curtain upstream of or around the dam through grouting, thereby changing seepage-field distribution, blocking water flow, reducing seepage pressure on the dam, decreasing seepage discharge, and ensuring dam safety. For the Daliuta Coal Mine underground reservoir in Ordos, Chen (2015) established a finite-element numerical model including coal-seam structures, mining-damaged zones, and different types of water-retaining dams. The seepage-field characteristics under three conditions, namely no curtain, a 3 m thick curtain, and a 5 m thick curtain, were compared. The results showed that a curtain-grouting anti-seepage system can effectively block upstream water and significantly reduce dam seepage, providing a specific scheme for anti-seepage curtain layout in engineering practice. Using the Lingxin Coal Mine in Ningxia as the background, Wu et al. (2021) combined solid-liquid coupled similarity-model tests with OpenGeoSys multi-field coupled numerical simulation to analyze the evolution of overburden fracture networks and diffusion paths of highly saline mine water under repeated mining. The study revealed that whether mining-induced fractures form connected seepage channels is the core factor controlling seepage-prevention effectiveness. Under water injection, highly concentrated brine mainly diffuses along fracture channels in the K4 aquifer and adjacent overburden, whereas appropriately configured geological barriers can effectively limit contamination of upper aquifers by highly saline water. Using the Chahasu Coal Mine in the Shendong mining area as a case study, Yu (2024) systematically studied the damage mechanism and seepage characteristics of coal-pillar dams under complex immersion conditions, established a mining-induced coal damage-permeability model considering triaxial stress, proposed a bearing-seepage zoning method for coal-pillar dams, and developed a zoned fluid-solid coupling model. This provides a theoretical basis for optimizing dam seepage-prevention measures and evaluating long-term stability from the perspective of coupled microscopic damage and macroscopic seepage.

4.3.2 Reasonable reservation and layout strategies for coal-pillar dams

The reserved size and spatial layout of coal-pillar dams have decisive effects on dam stability and safe reservoir operation. For the specific geological conditions of the Daliuta Coal Mine in the Shendong mining area, Wu (2018) used similarity-model tests to analyze the reservation mode and stability of coal-pillar

dams in distributed underground reservoirs. The study proposed that, in the direction parallel to the coal-seam plane, coal-pillar layout should satisfy the requirement that the height of the goaf fracture zone formed by working-face mining is slightly smaller than the spacing between two coal seams; in the direction perpendicular to the coal-seam plane, an aligned layout provides better stability. Using the Shigetai Coal Mine in the Shendong mining area as a case study, Xu et al. (2025a) established an evaluation system with four criterion layers and fourteen indicator layers, and used analytic hierarchy process and fuzzy theory to comprehensively evaluate coal-pillar dam stability. The study suggested that the reserved width of coal-pillar dams should be appropriately increased in future engineering design to cope with deterioration risks caused by long-term immersion, and that grouting reinforcement should be carried out promptly at identified leakage points.

Using the Lingxin Coal Mine in the Ningdong mining area as a case study, Wang (2022) investigated the damage mechanism of coal-pillar dams under long-term brine immersion and showed that salt ions reduce the surface tension between coal-rock particles, thereby weakening cohesion and causing deterioration of mechanical properties. This provides a basis for determining reasonable coal-pillar dam reservation parameters considering time-dependent deterioration. Using the Chahasu Coal Mine in the Shendong mining area as a case study, Yu (2024) further studied the water-absorption characteristics and mechanical-property deterioration of coal and rock under complex immersion conditions, established a damage-permeability model considering triaxial stress, proposed a bearing-seepage zoning method for coal-pillar dams, and developed a zoned fluid-solid coupling model that can be used to optimize coal-pillar dam stability assessment.

Overall, research has progressed from geometric-layout optimization to comprehensive evaluation of damage evolution and stability under multi-field coupling. The results show that reasonable reservation of coal-pillar dams must comprehensively consider mining-induced fracture development, long-term hydrochemical erosion, and stress-seepage coupling. Long-term safe operation of coal mine underground reservoirs can be ensured only by optimizing layout, reserving safety width, and implementing dynamic reinforcement measures.

5 Deep geological storage of mine water and water-quality safety

5.1 Technical system for deep geological storage of mine water

Direct utilization of highly saline mine water is difficult, leading to the development of deep geological storage technology. This technology injects highly saline mine water into independent deep low-permeability geological spaces to isolate it from shallow aquifers and the biosphere and prevent environmental pollution. Du et al. (2025) systematically described the feasibility and technical approach of deep geological storage of coal mine water (Fig. 6), proposed a full-process technical system covering basic theoretical research, technology and equipment development, and engineering application, and verified the scientific validity and safety of injecting highly saline

Tab. 2 Comparison of dam types and seepage-control measures for coal mine underground reservoirs

Type or measure	Structural or functional characteristics	Main advantages	Key limitations or failure risks	Evaluation and design focus
Artificial dam	Engineered structure connecting coal pillars and roadway or rock walls	Geometry, materials, and construction quality can be controlled	Local stress concentration, joint leakage, cracking, and water-head exceedance	Limit water head, weak zones, confining pressure, joints, and field validation
Coal-pillar dam	In-situ coal pillar retained as the principal water-retaining structure	Little additional construction and effective use of the existing mine layout	Long-term immersion, hydrochemical deterioration, mining disturbance, and fracture seepage	Pillar width and layout, damage evolution, permeability, and time-dependent stability
Dam-coal/rock connection zone (critical interface)	Artificial sealing or reinforced connection between coal pillars and surrounding rock	Combines in-situ bearing capacity with engineered seepage control	Interface debonding, stress concentration, and preferential leakage along contacts	Connection geometry, material compatibility, interface stress, and sealing integrity
Anti-seepage curtain (auxiliary measure)	Low-permeability grouted barrier installed upstream of or around the dam	Reduces seepage discharge and hydraulic pressure on the main dam	Effectiveness depends on curtain continuity and fracture-network connectivity	Curtain depth and thickness, grouting quality, seepage-field response, and long-term durability

mine water through deep wells into deep porous sandstone spaces for isolation from the biosphere using M Coal Mine in the Ordos Basin as an example. Liu and Dong (2026) further focused on the insufficient prediction accuracy of single-well storage capacity. Using sandstone from the Liujiagou Formation in well FC-01 in the Ordos Basin as the study material, they used sandstone physical-property tests, physical simulation, and numerical simulation to reveal that sandstone permeability gradually decreases with increasing effective stress. A theoretical model for single-well storage capacity considering permeability stress sensitivity was derived. The results showed that the model prediction differed from the measured value by only 3.70%, and that under constant-pressure injection mode only a small number of injection wells are needed to meet the mine-water storage demand of a ten-million-ton-per-year coal mine, substantially reducing engineering cost and verifying the economic feasibility of the technology.

5.2 Water-rock interaction mechanisms and mine-water purification

During operation of coal mine underground reservoirs, mineral components in roof-caved rocks and mine water undergo a series of complex physicochemical interactions, including dissolution, hydrolysis, and adsorption, which naturally purify mine water. Clarifying these mechanisms is central to ensuring reservoir water-quality safety. Zhang et al. showed that water-quality purification is mainly achieved through mineral dissolution, such as calcite and gypsum dissolution, adsorption, especially adsorption of Ca^{2+} and Mg^{2+} by mudstone and fine sandstone, ion exchange, and precipitation. Mudstone has the strongest adsorption capacity, whereas fine sandstone has stronger dissolution capacity (Zhang et al., 2024a,b). In addition to physicochemical processes, microbial communities, such as bacterial metabolic activities, also play important roles in degrading organic matter measured as COD and removing ammonia nitrogen. Studies indicate significant differences between microbial community structures in reservoir inflow and

outflow (Li et al., 2024).

Using the Daliuta Coal Mine underground reservoir as a case study, Fang et al. (2022) used advanced micro-characterization methods, including X-ray diffraction, X-ray fluorescence spectroscopy, scanning electron microscopy, and Fourier-transform infrared spectroscopy, to analyze the chemical composition and microstructure of roof-caved rock samples. Static indoor water-rock interaction experiments were then conducted to systematically reveal the intrinsic laws of water-rock interactions. Typical minerals in roof rock samples, including albite, potassium feldspar, kaolinite, illite, and chlorite, undergo hydrolysis reactions in mine water. The increase in potassium ion concentration in water mainly originates from hydrolysis of potassium feldspar and illite. Meanwhile, roof rock samples show significant adsorption effects on metal ions in mine water. The decrease in calcium ion concentration is mainly attributed to chlorite adsorption and calcium carbonate precipitation. Chlorite adsorption of calcium ions exhibits multilayer heterogeneous adsorption characteristics, with irregular adsorption sites and mutual interactions among sites. Studies confirm that water-quality purification is mainly achieved through mineral dissolution, such as calcite and gypsum dissolution, adsorption, especially adsorption of Ca^{2+} and Mg^{2+} by mudstone and fine sandstone, ion exchange, and precipitation. Mudstone has the strongest adsorption capacity, whereas fine sandstone has stronger dissolution capacity (Zhang et al., 2024a,b).

This study provided an initial explanation of the intrinsic mechanisms by which roof rock samples purify mine water through mineral dissolution, hydrolysis, and adsorption, providing a sound theoretical basis for optimizing the selection of water-storage-layer materials and ensuring water-quality safety.

In addition to the self-purification effect of naturally caved rock masses, the particle-size gradation of water-storage materials also significantly affects water-quality purification. Different gradations alter key water-quality indicators of pit water, including turbidity, hardness, and heavy-metal content, through the combined effects of physical filtration and chem-

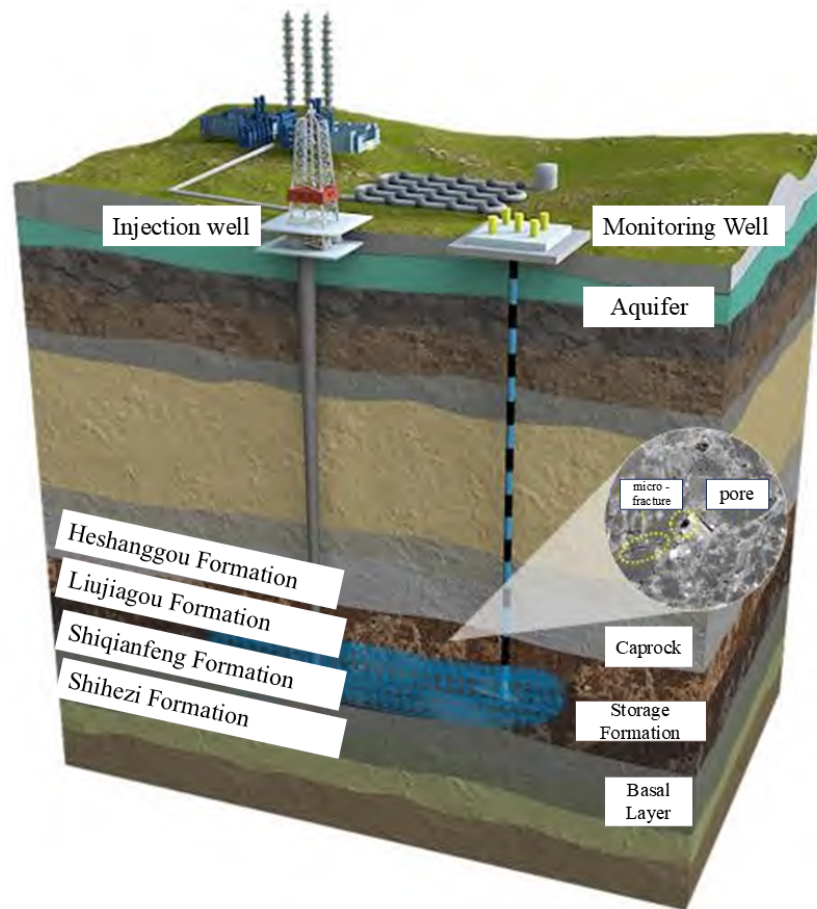


Fig. 6 Conceptual model of deep geological well injection and storage of mine water (Du et al., 2025)

ical adsorption. Cao (2021) conducted a dedicated study on the characteristics of the water-storage layer in open-pit mine underground reservoirs. Undisturbed sandstone and two sandstone gradations with particle sizes greater than 2 mm and greater than 10 mm were selected as storage materials. Similarity simulation tests were used to analyze the influence of different gradations on pit-water quality. Eight core water-quality indicators were monitored, namely turbidity, hardness, chemical oxygen demand, ammonia nitrogen, nitrite, electrical conductivity, pH, and heavy-metal content. The results showed that, after preliminary cleaning treatment of pit water, sandstone with particle sizes greater than 2 mm provides the advantages of small displacement variation, high storage coefficient, and fast seepage velocity, achieving the best storage and water-quality assurance effects. Fang et al. (2022) further confirmed through their study of naturally caved rock masses at the Daliuta Coal Mine that the mineral composition and physical structure of storage materials directly determine mine-water purification efficiency, and that adsorption by minerals such as chlorite is an important mechanism for ensuring water-quality safety.

Overall, the available evidence indicates that the particle-size gradation and mineral composition of water-storage materials directly determine mine-water purification efficiency. Sandstone with a 2 mm gradation can effectively balance water-storage performance and water-quality purification, and miner-

al adsorption by naturally caved rock masses can also significantly improve water quality. Future research should further quantify water-quality evolution laws for materials with different gradations under long-term operation, providing a more precise basis for water-storage-layer design.

5.3 Environmental risks and diffusion laws of highly saline mine-water storage

5.3.1 Transport-channel characteristics of highly saline water in mining-induced fracture networks

Coal mining induces mining-related fracture networks in the overlying strata. These networks directly control the migration pathways and diffusion ranges of highly saline mine water in underground spaces, and therefore determine its potential contamination risk to surrounding aquifers. Using the Lingxin Coal Mine in Ningxia as a case study, Wu et al. (2021) combined solid-liquid coupled similarity-model tests with numerical calculation to reveal the evolution of overburden fracture networks in goafs under repeated mining. The study found that after high-concentration brine is injected, it first flows along fracture-rich goaf zones and then gradually diffuses upward into overlying aquifers through fractures. Within 50 years, only trace amounts of highly saline water diffuse into deeper aquifers, and the diffusion range is mainly concentrated in specific aquifers and their adjacent overburden, demonstrating that fracture-channel

connectivity directly determines the contamination diffusion range of highly saline water. Yu (2024) systematically studied the water-absorption characteristics and damage mechanisms of coal and rock under complex immersion conditions through field investigation, laboratory tests, and numerical simulation. A mining-induced coal damage-permeability model and a zoned fluid-solid coupling model considering triaxial stress were established, revealing the law of trace water migration and diffusion within macroscopic water-resisting zones. The study indicated that the permeability characteristics of mining-induced fracture networks dynamically evolve with coal deterioration under coupled stress, seepage, and water-damage effects. This dynamic evolution directly affects transport-channel characteristics of highly saline water, and risk changes caused by channel evolution must be considered during long-term operation.

Collectively, these studies show that mining-induced fracture networks are the main channels for highly saline water migration, and that their evolution is jointly controlled by mining disturbance and water-rock interaction. Future research should further combine multi-field coupled simulation with long-term field monitoring to accurately predict the long-term migration behavior of highly saline water in complex fracture networks and provide more reliable theoretical support for safe mine-water storage.

5.3.2 Spatiotemporal evolution of concentration fields and pollution-risk assessment for overlying aquifers

The spatial evolution of solute concentration fields over time, together with the pollution-risk level and influence range of highly saline water diffusion on overlying aquifers, constitutes a central component of environmental risk assessment for highly saline mine-water storage. Using the Lingxin Coal Mine underground reservoir in Ningxia as a case study, Wu et al. (2021) combined solid-liquid coupled similarity-model tests with OpenGeoSys multi-field coupled numerical simulation to study overburden fracture-network evolution and seepage-diffusion characteristics of highly saline mine water in goafs under repeated mining. The results showed that high-concentration brine enters the K4 aquifer along overburden fractures. Within 50 years, the concentration field mainly diffuses within the K4 aquifer and adjacent overburden, with only trace diffusion into the overlying K3 aquifer. This demonstrates the decisive role of mining-induced fracture connectivity in pollution risk, and indicates that reasonably designed dams and barriers can confine highly saline water to a specific range. Wang (2022) focused on the damage mechanism of coal-pillar dams under long-term brine immersion and established an ion diffusion-transport model considering salt-solution deterioration effects through laboratory tests and numerical simulation. The study found that salt-ion diffusion weakens cohesion between coal-rock particles and that the physical and mechanical properties of coal and rock decrease logarithmically with immersion time. This explained, at the microscopic mechanism level, the long-term influence of water-rock interaction on dam seepage-prevention stability, and clarified that salt-ion diffusion into dams affects not only water quality but also dam safety. Using the Chahasu Coal Mine in the Shendong mining

area as a case study, Yu (2024) systematically studied the water-absorption characteristics and multi-scale structural damage evolution of coal and rock under complex immersion conditions, established a mining-induced coal damage-permeability model considering triaxial stress, proposed a bearing-seepage zoning method for coal-pillar dams, and quantitatively characterized the trace migration and diffusion of water within macroscopic water-resisting zones, further refining the spatiotemporal evolution mechanism of concentration fields inside coal-pillar dams.

Overall, existing research has characterized the evolution laws of highly saline mine-water concentration fields from multiple dimensions, including fracture-network seepage channels, microscopic coal-rock damage and deterioration, and macroscopic seepage zoning. The results indicate that although highly saline mine water may diffuse upward along mining-induced fractures and cause pollution, rational dam design and geological barrier control can effectively limit the diffusion range and ensure the water-quality safety of overlying aquifers.

6 Expansion of engineering applications and future prospects of underground reservoirs

6.1 Coupled utilization of abandoned-mine pumped storage and underground reservoirs

Over nearly two decades of development, China has achieved major advances in accurate storage-capacity calculation, dam-stability optimization, and water-quality control for coal mine underground reservoirs, thereby laying a solid foundation for safe and reliable underground water-storage systems. The functions of coal mine underground reservoirs can therefore be expanded further. By exploiting their substantial vertical elevation differences and enclosed storage spaces, their conventional role in mine-water storage can be extended to a multifunctional system that integrates water-resource regulation with flexible energy regulation. Such a system could support grid peak shaving by using surplus renewable electricity for pumping during low-load periods and releasing water for power generation during peak demand. This approach could simultaneously alleviate water scarcity and diversify the energy structure of western mining areas, enable the beneficial reuse of abandoned underground spaces, and substantially increase the resource value of closed mines; it has consequently become an important direction in abandoned-mine utilization. Schmidt et al. demonstrated the technical feasibility of constructing compressed-air energy-storage systems in roadways of closed deep coal mines, particularly when circular concrete linings with sealing layers are used to control deformation effectively (Schmidt et al., 2024). Figure 7 presents a schematic diagram of the proposed 200 MW pumped-storage hydropower station in the abandoned Prosper-Haniel coal mine in Germany. The project has been described as the first conversion of an abandoned coal mine into an energy-storage power station and is intended to store surplus wind and solar energy.

Existing research indicates that converting abandoned goafs into pumped-storage power stations has considerable value for resource recovery. The life-cycle cost of such projects depends on multiple factors, including initial retrofit investment

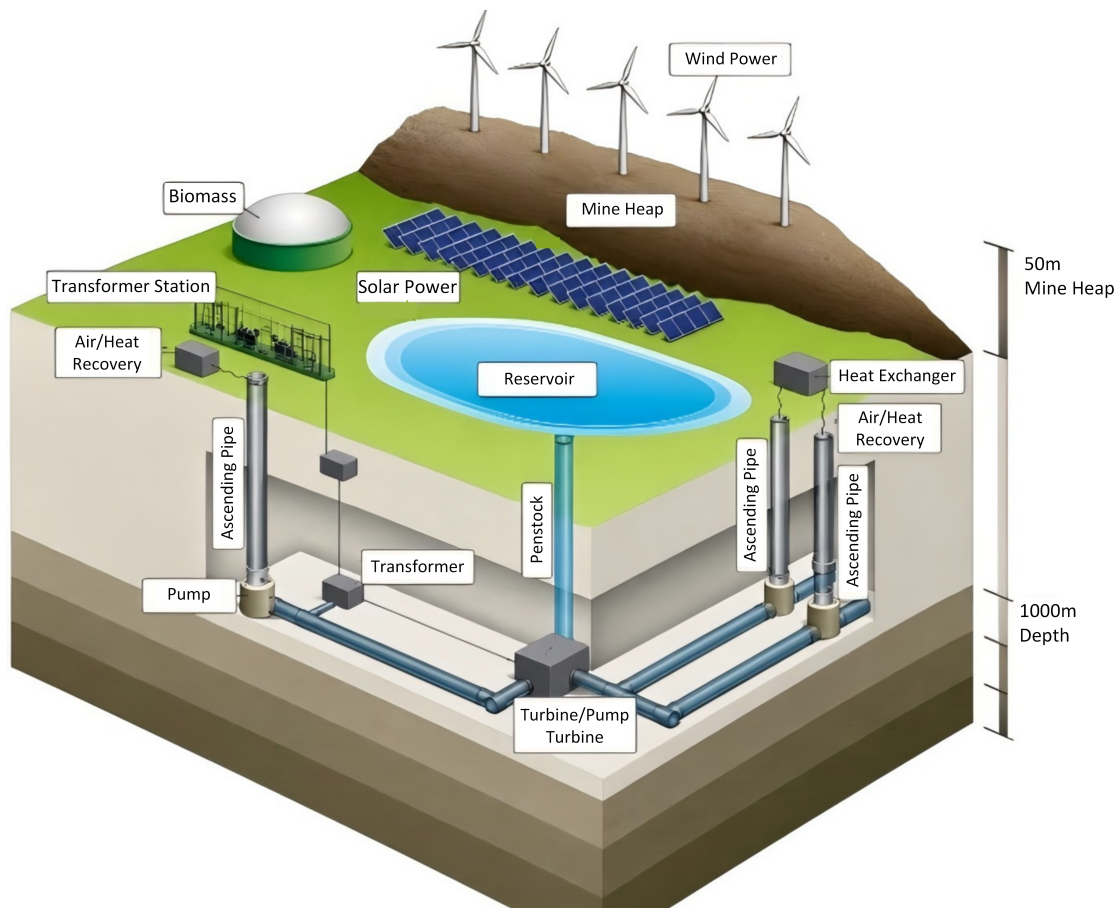


Fig. 7 Conceptual layout of the proposed underground pumped-storage hydropower station at the abandoned Prosper-Haniel coal mine

t, equipment selection, operation and maintenance efficiency, and the hydrogeological conditions of the mining area. Compared with newly constructed surface pumped-storage plants, these projects can substantially reduce the costs associated with reservoir inundation and resettlement, thereby providing a clear cost advantage. Although the principal technologies are already available, long-term economic evaluation and quantitative risk assessment of pumped-storage systems under deep and complex stress conditions remain inadequate. Future research should address three priorities. First, dynamic life-cycle cost models incorporating multi-field coupling among seepage, stress, damage, and electrical energy conversion should be developed to estimate project returns accurately. Second, economic analyses of the synergy between highly saline mine-water storage and pumped storage should be strengthened to determine the economic boundaries of projects at different scales. Third, standardized pathways for integrated water-energy-mining development in water-deficient western mining areas should be explored to achieve the dual objectives of efficient water-resource use and optimization of the regional energy structure. Moreover, because underground reservoirs provide effective thermal insulation, cross-seasonal hot-water storage, in which heat is stored in summer and used in winter, has been reported to achieve high thermal-storage efficiency (Wang et al., 2025). A complementary multi-energy develop-

ment model integrating underground reservoirs, pumped storage, and deep geothermal energy could therefore be explored. By building on the spatial and engineering infrastructure of underground reservoirs, geothermal resources could be developed concurrently, facilitating the transformation of abandoned mines into integrated energy bases.

To provide quantitative context for pumped-storage coupling, Fan et al. (2020b) developed a representative hybrid pumped-hydro model using abandoned coal-mine goafs. Under the assumed mine geometry and operating conditions, the model estimated a usable reservoir volume of $1.58 \times 10^6 \text{ m}^3$, an average system efficiency of approximately 82.8%, and a regulating-energy density of 1.06 kWh/m^3 . These values are model estimates rather than measurements from an operating commercial plant. The same analysis showed that effective cyclic operation depends on maintaining goaf permeability above 10^{-7} m^2 , preserving a usable coefficient of at least 0.8, limiting inter-reservoir leakage to below 1%, and controlling ventilation-shaft pressure loss. These parameters identify concrete operational bottlenecks involving hydraulic connectivity, leakage control, reservoir spacing, and air-pressure management, all of which require field-scale verification before commercial deployment.

Hydrogen storage requires a stricter containment boundary than water storage. A recent review comparing lined rock cav-

erns with abandoned mines concluded that abandoned mine voids commonly present uncertain geotechnical stability, complex sealing requirements, groundwater connections, and elevated leakage risk, whereas purpose-built lined rock caverns rely on engineered multi-layer barriers and controlled pressure management (Hawez et al., 2026). On this evidence, a conservative coupling concept for coal mine underground reservoirs is to use the water reservoir to support electrolysis, cooling, and water-resource regulation, while storing hydrogen in a physically isolated salt cavern or purpose-built lined rock cavern rather than directly in a water-filled goaf. The principal research requirements are cyclic sealing integrity, hydrogen-embrittlement resistance, leakage monitoring, and the coupled effects of hydrogen-rock-microbe interactions.

For multi-energy coordination, the performance variables reported in existing studies can be organized into a common dispatch and evaluation framework. Pumped-storage assessment should include usable storage volume, round-trip efficiency, hydraulic loss, and leakage; compressed-air and hydrogen storage should include allowable pressure, liner deformation, gas tightness, and leakage; thermal storage should include recoverable heat, storage efficiency, and heat loss; and the primary water-storage function should retain constraints on reservoir water level, dam deformation, seepage, and water quality. A coordinated dispatch model should treat these safety and performance variables as explicit operating constraints rather than simply adding the nominal capacities of individual technologies (Fan et al., 2020b; Schmidt et al., 2024; Wang et al., 2025; Hawez et al., 2026).

6.2 Engineering practice and demonstration effects in typical mining areas

Representative coal mine underground-reservoir projects have been constructed at the Daliuta and Shigetai coal mines in the Shendong mining area, and the distributed layout of the Daliuta underground-reservoir system is illustrated in Fig. 8. These demonstration projects have not only verified the technical feasibility of constructing coal mine underground reservoirs in mining-induced overburden separation zones and goafs, but have also generated valuable engineering experience in accurate storage-capacity calculation, dam-stability control, and the safe storage of highly saline water. They therefore provide replicable and scalable examples of mine-water utilization in the water-deficient coal-mining regions of western China. Nevertheless, existing research and engineering practice continue to reveal theoretical gaps and technical constraints concerning the long-term evolution of dam damage under multi-field coupling, quantitative environmental-risk assessment for high-concentration mine-water storage, and the coordinated optimization of coal mine underground reservoirs with emerging energy systems such as pumped storage. Further advances are therefore required.

Representative coal mine underground-reservoir projects are concentrated in the Shendong mining area of Inner Mongolia and Shaanxi, with additional demonstrations in Ningdong, Ningxia, and nearby western coal bases. The cases differ in reporting basis: some provide reservoir volume, some report

water flow or demand coverage, and others report structural safety. Table 3 therefore compares only values explicitly reported in the cited studies and avoids converting unlike indicators into a single ranking.

For open-pit coal mines in the water-deficient regions of western China, existing studies indicate that distributed underground reservoirs constructed in large goafs or abandoned pits offer substantial spatial and ecological advantages, despite extensive surface disturbance, complex groundwater systems, and fragile ecological conditions. On the one hand, open-pit mine voids provide large storage spaces without requiring additional excavation. On the other hand, underground storage reduces evaporation losses and is therefore well suited to the arid climate of western China. Nevertheless, three major constraints remain. First, the coupling between open-pit slope stability and underground water-storage systems is not yet fully understood, and slope instability may directly threaten reservoir safety. Second, mine water in arid western regions is generally highly mineralized, while safety-assessment and risk-control technologies for its long-term storage remain incomplete. Third, dynamic capacity-regulation technologies for extreme droughts and rainstorms are not sufficiently mature to address the challenges posed by climate change. Future research should establish multi-field coupled stability-assessment systems for open-pit mines and underground reservoirs, develop new seepage-control and water-purification materials suitable for high-salinity and high-permeability environments, and further improve coordinated water-energy-mining development. These efforts would support the integrated storage, safe utilization, and ecological restoration of water resources in mining areas.

6.3 Research challenges and future development directions

Research on coal mine underground reservoirs in China has made substantial progress in storage-space characterization, accurate capacity calculation, dam-stability mechanisms, and water-quality control. Demonstration projects in Shendong and other mining areas have verified the technical and economic feasibility of this approach. However, significant limitations remain under deep and complex geological conditions and over the long periods required for reservoir operation.

The first research priority is long-term safety monitoring under complex multi-field coupling. Most existing monitoring technologies are static and cannot adequately capture the dynamic evolution of dam damage and seepage under coupled deep stress, hydraulic, and chemical conditions. Future work should address these limitations by developing intelligent sensing networks that integrate fiber-optic sensing, microseismic monitoring, and digital-twin technologies. Such networks should provide real-time early warning of dam-damage initiation and propagation, changes in fracture-controlled seepage, and anomalies in reservoir water quality, while supporting life-cycle safety assessment. This capability would provide technical support for the large-scale, safe, and sustainable utilization of mine-water resources.

The second research priority is coordinated water-heat-

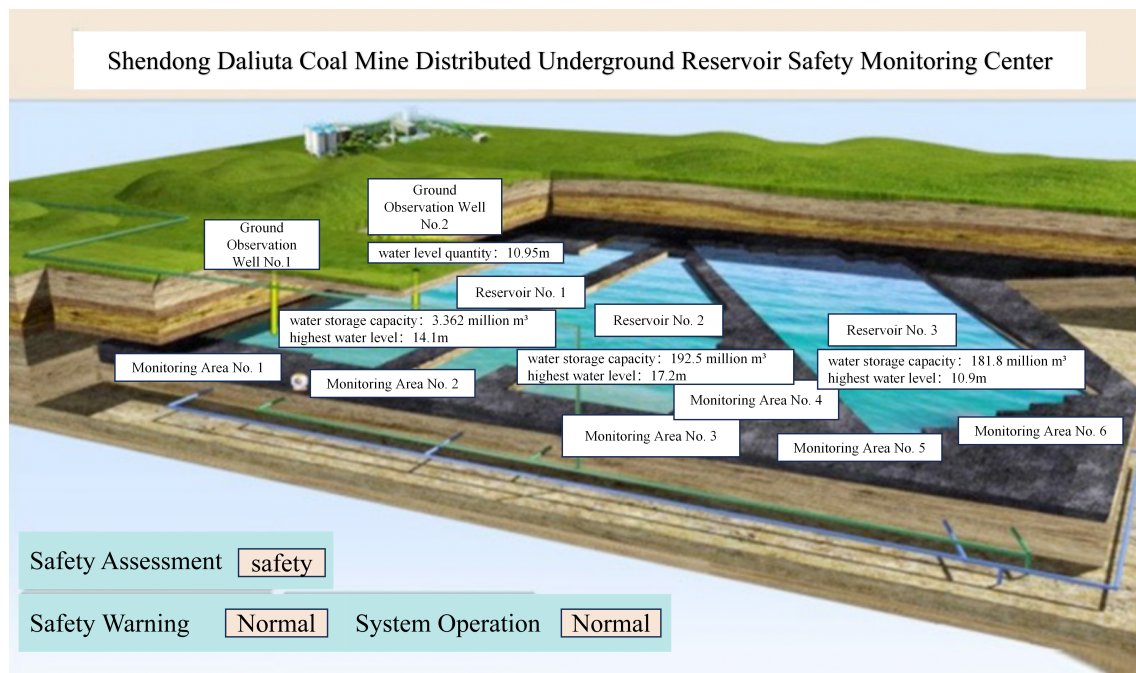


Fig. 8 Schematic diagram of the distributed underground reservoir at Daliuta Coal Mine, Shendong

Tab. 3 Quantitative evidence from representative coal mine underground-reservoir demonstrations

Case and location	Scale or operating record	Reported performance or validation
Case and location	Scale or operating record	Reported performance or validation
Shendong reservoir cluster, Inner Mongolia-Shaanxi	32 reservoirs reported at regional scale	Approximately 95% of total water demand covered
Daliuta Coal Mine, Shendong	Three operating reservoirs	Total storage capacity of approximately $7.105 \times 10^6 \text{ m}^3$
Buertai Coal Mine, Inner Mongolia	Reservoir inflow remained above $500 \text{ m}^3/\text{h}$ during 3.5 years of observation	Mine industrial and domestic demand $141.9 \text{ m}^3/\text{h}$
Lijiahao Coal Mine, Inner Mongolia	Artificial-dam limiting water head calculated as 17.8 m	Field measurements agreed with numerical assessment

Note: Reported indicators are not fully standardized across projects; values are reproduced on the basis used in the cited studies. The cases provide different forms of evidence. Shendong reports regional demand coverage, Daliuta reports total storage capacity, Buertai reports inflow, mine-water demand, and a potential irrigation area, and Lijiahao provides agreement between the calculated limiting water head and field measurements. Because these indicators describe different aspects of performance, the cases are presented without a combined ranking.

energy development to expand the functional value of coal mine underground reservoirs. Most existing studies focus on the storage and utilization of water resources as a single function and have not fully examined the heat-storage potential of deep goafs and underground reservoirs. Future research should extend this conventional perspective by closely integrating mine-water storage with the development of deep geothermal resources. On the one hand, stored highly mineralized mine water could serve as an efficient heat-transfer medium in a closed-loop system that extracts heat from the deep lithosphere, thereby enabling heat recovery while supporting system stability. This approach could provide clean energy while maintaining the stability of underground stress and seepage fields through controlled water circulation. On the other hand, several key scientific questions must be addressed, including long-term safety monitoring under thermo-hydro-mechanical-chemical coupling, the effects

of thermal-hydrochemical interactions on dam stability, and economic-evaluation models for coordinated development. Ultimately, an integrated water-heat-energy framework for green mines should be established to provide new theoretical and technical pathways for the comprehensive and efficient utilization of abandoned-mine resources..

7 Conclusions

As an innovative model of mine water management that integrates “diversion, storage and utilization”, coal mine underground reservoirs have become a key technical approach to realize water-preserved coal mining and coordinated development of coal development and ecological protection in arid and semi-arid mining areas. This paper systematically sorts out the theoretical development and technical progress of coal mine underground reservoirs in China, and the main conclusions are as follows:

(1) After years of theoretical exploration and engineering practice, China has formed a complete theoretical framework and key technical system for coal mine underground reservoirs, covering reservoir site selection, effective storage capacity calculation, coal pillar dam stability control, seepage risk prevention and other core links. Research advances including storage space characterization based on overburden movement trajectories and multi-field coupled dam damage evolution models have significantly improved the scientificity and engineering reliability of underground reservoir design. The construction of demonstration projects in western mining areas such as Shendong has verified that this technology has outstanding advantages such as no occupation of surface land, low construction cost and natural purification of water quality, and has achieved remarkable economic and ecological benefits.

(2) Deep geological storage of mine water based on underground reservoirs shows great application potential in the disposal of high-salinity mine water and the control of environmental risks. It can realize the safe isolation of high-salt mine water that is difficult to treat centrally on the surface, which effectively reduces the risk of salt diffusion and groundwater pollution, and provides a feasible solution for the green development of high-salt mining areas in western China.

At present, the promotion of coal mine underground reservoir technology under deep and complex geological conditions still faces bottlenecks such as insufficient dynamic characterization of storage space, unclear long-term damage mechanism of water-retaining dams, and imperfect risk prevention system for high-salinity water storage. Future research should focus on two core directions: first, develop long-term safety monitoring and early warning technology for coal pillar dams under complex multi-field coupling of stress, seepage and corrosion, to reveal the long-term evolution law of dam stability; second, promote the integrated development of coal mine underground reservoirs and pumped storage, carbon geological storage and other new energy development and green carbon sink projects, to expand the multi-functional value of coal mine underground reservoirs and promote the green transformation and sustainable development of coal industry in China.

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Conflict of interest

The authors declare no competing interest.

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