Mine Water Injection and Storage in Ordos Basin, China

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Abstract

This paper explores the application of mine water injection and storage technology in the Ordos Basin, focusing on its hydro-geological framework and practical implementation strategies. 15 hydro-geological frameworks of mine water injection and storage are systematically delineated. The sandstone and limestone types are categorized and described. Based on projects, the study also evaluates six different well construction methods and operational modes. And the case study of the MC-1 well in the Muduchaideng coal mine provides insights into the challenges and successes of long-term mine water injection. The detailed implementation plans, hydro-geological testing, operation timelines and consideration for re-operation were presented to provide the option methodology for sustainable mine water resource management in the arid and semi-arid areas.

Keywords: Mine water injection, storage, hydro-geological framework, mode

Introduction

Ordos Basin is currently the most important coal resource base for China. The Jurassic coal measures are widely mined for energy supply. Huge roof sandstone water drainage induced by mining activities is drained due to the typical hydro-geological framework. The total amount of mine water drainage nearly is 50% of the regional water consumption (Chen *et al.* 2020). Managed Aquifer Recharge (MAR) is generally adopted in the over-abstraction of groundwater, CO_2 storage, oil and gas recovery, salt mining, surface subsidence, saltwater intrusion and so on. Mine water injection and storage is a method that similar to the MAR, but the main and key technique is different from this conventional approach. According to an inventory of 27 mines using or considering MAR for current or future operations in the review paper (Sloan *et al.* 2023), only Garzweiler open coal mine at Rhine land area of German is one project in the coal field, the others are all referring to metallic mines (Yungwirth *et al.* 2017). While some public papers have explored the geological storage of mine water (Chen *et al.* 2022; Chen *et al.* 2022; Chen *et al.* 2022; Li *et al.* 2024; Li *et al.* 2024), a systematic exploration of the hydro-geological framework and geological storage mode remains a critical research priority, necessitating further interdisciplinary studies to address unsolved complexities. This paper systematically delineates the aforementioned research components through theoretical analysis, laboratory experiment and empirical projects validation.

Materials and methods

The concept of coal mine water injection and storage

Mine water injection and storage is a treatment method for mine water that is coming to the mining space by the disturbances of coal resource extraction. Water will be injected and stored in the deep underground space of these strata through artificial interventions or the nature-based function of the hydro-geological framework in the coal mine. Generally, when the target aquifer is deeper than the coal measures, the model will be qualified as deep injection and storage.

Key elements, guiding principles and technical characteristics are summarized based on the existing engineering cases. Key elements include mine water sources, deep-storage pathways, deep-storage spaces and impermeable caprocks. Guiding principles include Coal mine safety prioritization, environmental protection through quality-stratified storage and resource exploitation compatibility. Technical characteristics include water quality stability, adequate reservoir capacity, controllable permeability and cost-effectiveness.

The hydro-geological framework of mine water injection and storage in China

The hydro-geological framework (Kihm *et al.* 2024) of mine water injection and storage specifically refers to the spatial positions and combinational relationships among the target aquifers (categorized as shallow, deep, and those at the same layer), the coal seams being mined or already mined , the deep storage sites (surface or underground), as well as the aquifers and aquitards at different depths, various water filling sources (such as water inrush bodies) in the mine, the pathways (channels and wells), the hydro-geological boundaries, the mining spaces, etc. The spatial arrangements and combinational relationships of those elements collectively determine the effectiveness and safety of mine water injection and storage.

Drawing on the extant mine water injection and storage projects, the author has meticulously collated and comprehensively summarized the types of hydro-geological framework associated with mine water injection and storage in China. The detailed information is explicitly presented in Table 1.

Typical hydro-geological framework of mine water injection and storage in the deep sandstone aquifer

The hydro-geological framework for mine water injection and storage in the deep sandstone aquifer in the Ordos Basin is as follows: Groundwater from Yan'an Formation (with a TDS content of 7000 mg/L to 9000 mg/L) and Zhiluo Formation (with a TDS content of 1000 mg/L to 3000 mg/L) within the vertical scope of caving zone and water-conducting fracture zone induced by mining activities for No.3 coal seam of Yan'an Formation, will flow through the mining-induced fractures or drainage boreholes to the surface/ underground ponds by the drainage system. The mine water will be injected and stored in the Triassic Liujiagou Formation sandstone aquifers by deep wells (such as vertical, inclined and branch wells).

Different well structures and modes for mine water injection and storage in Ordos Basin

The implementation of mine water injection and storage projects in Muduchaideng mine, Nalinhe No.2 mine and Dahaize mine shows that 6 applicable well constructions for sandstone mode are summarized as shown in Figure 2.

The mine water injection and storage has been applied in some coal mines with different modes, which is determined by the TDS content of mine water, well structure, injection flow, wellhead pressure, injection time and frequency as well as the permeability & capacity increasing condition of the target aquifers. The projects of mine water injection and storage in the Muduchaideng mine and Nalinhe No. 2 are classified as the type of high TDS content, moderate flow rate and high pressure. Based on field trials and risk assessments, the solution is validated as technically feasible with safety parameters within acceptable thresholds.

Table 1 The hydro-geological framework of mine water injection and storage in China..

Water-inrush body in coal mines	The target layers of mine water injection and storage	Type description	Remarks
Surface water	Unconsolidated aquifer Sandstone aquifer Karst aquifer Burnt rocks Unconsolidated aquifer	Surface water into the deep unconsolidated aquifer Surface water into the deep sandstone aquifer Surface water into karst aquifer Surface water into the deep burnt-rocks Quaternary water into the unconsolidated aquifer	Zhanihe coal mine
Groundwater from roof aquifer of coal seams	Sandstone aquifer Delamination space induced by mining activities Unconsolidated aquifer Sandstone aquifer	Roof sandstone water into another sandstone aquifer Roof sandstone water into the delamination space Sandstone water into the unconsolidated aquifer Limestone water into the unconsolidated aquifer Sandstone water into the deep sandstone aquifer	A specific coal mine in Maowusu deset of Ordos basin Muduchaideng mine, Nalinhe No. 2 mine, Mataihao mine, Dahaize mine and Xiaobaodang mine
Groundwater from floor aquifer of coal seams	Karst aquifer Mixed aquifer Roof goaf	Limestone water into the deep sandstone aquifer Sandstone water into the deep aquifers of Taiyuan Formation, Ordovician, and Cambrian limestone Limestone water into the deep aquifers of Taiyuan Formation, Ordovician, and Cambrian limestone Sandstone water into the deep mixed aquifers of sandstone and limestone Goaf water into the roof goad	Lilou mine-Wutongzhuang mine and Xiaoyun coal mine Laoyingyan coal mine
Goaf water in the same coal seams	Goal in the same level Floor goaf	Goal water into another goaf of the same level Goaf water into the floor goaf	Underground reservoirs in mines, Lingxin coal mine
Other types	Burnt-rock aquifer	Water-inrush body into the burnt-rock aquifers	Shendong mining area

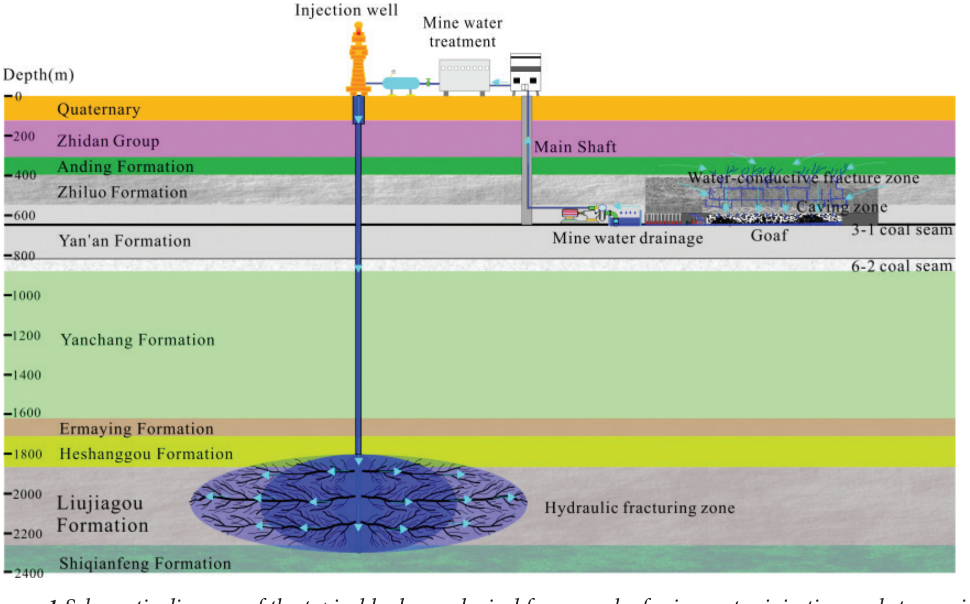

Figure 1 Schematic diagram of the typical hydro-geological framework of mine water injection and storage in the deep sandstone aquifer.

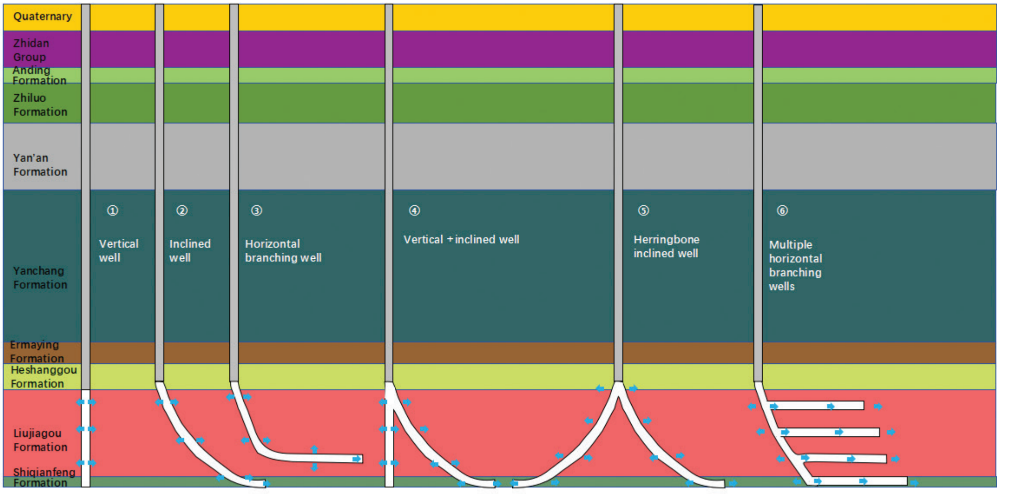

***Figure 2** Different well constructions for mine water injection and storage.*

Results and discussion

Construction of MC-1 well and in-situ hydro-geological testing in Muduchaideng coal mine

The MC-1 well was constructed from 1st October 2019 to 8th March 2020, with a total length of 2299.5 m. The target Liujiagou Formation was buried from 1800 m to 2290 m, with 113 sub-layers. The typical lithology was characterized by the brown, pinkish-red, red and gray sandstone and mudstone. Due to the low-porosity and low-permeability for this tight target layer, the conventional pumping tests were infeasible (flow rates too low) , prompting a shift to the natural water-level recovery test, which further confirmed the low-permeability characteristics. The original Liujiagou Formation was low porosity at 7.5% and lower permeability at 5.31×10^{-6} m/d to 6.19×10^{-6} m/d. Subsequent variable-pressure injection tests were conducted to derive hydro-geological parameters. After hydraulic fracturing, the permeability significantly greater 1788 to 2858 times greater than natural. We found that the critical pressure of hydraulic fracturing should be greater than 31.5 MPa.

Operation of mine water injection and storage from March 2020 to July 2021

Observations of injection flow rates and pressures during March 2020 to July 2021, revealed persistent dynamic variations, indicating that under high-pressure and large-volume re-injection conditions, the fracture network within the deep target layer remained in a state of continuous evolution. The fracture network was comprised with natural fractures and hydraulic fractures. The limited storage capacity of the reservoir necessitated repeated hydraulic fracturing to induce rock damage, thereby utilizing hydraulic pressure to gradually displace water radially, expanding the influence radius and creating additional storage space for mine water.

As demonstrated by the trend analysis of wellhead pressure versus injection flow rate (Figure 3), the wellhead pressure dynamics exhibited a gradual stabilization from an initial 6.2 MPa to a final equilibrium of 8.0 MPa, indicating progressive pressure buildup under controlled injection conditions. The flow rate demonstrated a sustained increase from 54 m^3/h to a steady-state plateau at 98 m^3/h, reflecting optimized hydraulic conductivity by hydraulic fracturing or operational adjustments. During this period, the cumulative mine water injection volume exceeded 1 million cubic meters, demonstrating significant sequestration potential. Storage and containment of mine water resources were partially achieved, enabling large-scale hydraulic management. Mine water treatment costs per ton were reduced by 80% through optimized injection protocols.

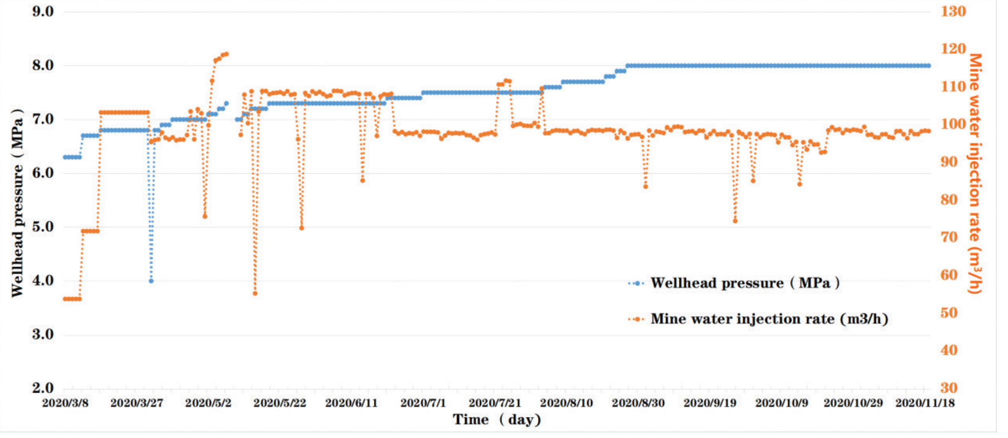

Figure 3 *Wellhead pressure and injection flow rate for MC-1 well.*

Operation from October 2024 to now

Prior to re-operation of MC-1 well, controlled water release was conducted by adjusting the valves at a flow rate of 100 to 200 m^3/h. Water quality analysis indicated that the TDS concentration exceeding 10,000 mg/L, but different from the original baseline of 65,111 mg/L for Liujiagou Formation water. The water temperature was recorded at 64 °C, which corresponded to a burial depth of approximately 2,100 – 2,200 meters from the previous logging data from MC-1 well. It was observed that there was no reduction in water discharge, so the professional oilfield service crew was engaged to perform the modification work on the MC-1 well. The cumulative volume of water release reached approximately 1,340,000 m^3.

The MC-1 well commenced re-injection on 4th October 2024, until now, a cumulative volume of 88,000 m^3 mine water had been injected. The typical operating wellhead pressure (at the roadway of -600 m level) ranged from 16 MPa to 18 MPa, accompanied by a flow rate from 60 m^3/h to 70 m^3/h. When the wellhead pressure was up to 22 MPa, the injection flow rate would decline to 50–60 m^3/h. We considered that the intermittent re-injection might induce sandstone fracture closure and re-opening. The existing fracture network and pores were saturated with high-pressure water, limiting the storage capacity. Elevated wellhead pressure could force new fractures to initiate based on the natural fracture network. High-pressure mine water may preferentially migrate along dominant fracture pathways (such as natural fractures), forming a hydraulic barrier when encountering low-permeability interlayers (such as mudstone).

Conclusions

The definition of mine water injection and storage was presented and 15 hydro-geological frameworks of in China were illustrated, especially the deep sandstone and limestone types were indicated with the operated project. As for the project of MC-1 well, the detailed implementation plans, hydro-geological testing, operation timelines and consideration for re-operation were presented to assess the feasibility and expectation of this proposed methodology.

Acknowledgements

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