Mine Water and the Environment (2024) 43:168–182
https://doi.org/10.1007/s10230-024-00977-3

TECHNICAL ARTICLE

Feasibility of Injecting Pretreated Mine Water into a Deep Ordovician Aquifer in the Lilou Coal Mine, China

Xin Li[1] · Ge Chen[1] · Wei Wei[2] · Xianfeng Tan[3,4] · Zhimin Xu[1,5] · Li Zhang[1] · Feng Zhang[3,4] · Qi Liu[1] · Yajun Sun[1,5]

Received: 20 June 2023 / Accepted: 10 February 2024 / Published online: 25 March 2024

Abstract
The groundwater quality in the Lilou Coal Mine in Shandong Province can be divided into "three zones" based on the range of mining-induced fractures. Considering the observed Ordovician aquifer water level decline rate of 2.6 m/year, we propose that the saline mine water contained in Zones II and III can be injected into the well-developed underling karst Ordovician aquifer in Zone I. A water quality comparison of 27 factors demonstrated that only the Na^+ concentration in the mine water exceeded that in the Ordovician aquifer water. The Ordovician aquifer has an average karst development thickness of 140 m, and the karst fracture rate ranges from 6 to 14%. The filter screen length of the injection well should reach 150 m to achieve zero pressure at the surface for an injection flow rate of 200 m^3/h. With only the need to reduce Na^+ concentrations below 319 mg/L, ≈ $2.4 million (U.S.) could be saved annually by simplifying the mine water treatment process.

Keywords Eastern China coal mine areas · Saline coal mine water (SCMW) · Ordovician aquifer recharge · In situ mine water injection · Hydrodynamic field evolution

Introduction

Untreated saline coal mine water that is directly discharged at the surface not only wastes groundwater, but also threatens the surface water ecological environment through the release of contaminants into rivers and lakes, soil salinization, land degradation, shallow unconfined aquifer pollution, and other problems (Chandra et al. 2023; Yajun et al. 2021). China's Shandong Province (Fig. 1a) is rich in coal resources. The aquifers in the coal roof and floor are mainly water-rich confined aquifers. Water-conducting structures such as faults and karst collapse columns connected with coal are developed in deeply buried Ordovician aquifers; a conceptual model is shown in Fig. 2. Mine water there typically exhibits elevated salinity levels, and most of the TDS (total dissolved solids) values exceed 1000 mg/L (i.e. saline coal mine water or SCMW). SCMW has consistently been regarded as a threat to mining practices. At present, coal enterprises mainly focus on low-cost, large-scale SCMW advanced desalination technologies. Ideally, treated mine water should be reused after attaining the recycled water quality requirements, but the cost of desalination ranges from ≈ $1.2–2.9 U.S. per tonne in China (Sun et al. 2022; Yajun et al. 2021). In addition to the high capital investment, there are a series of complex secondary problems in the large-scale application of advanced desalination technologies (Kang and Cao 2014).

In this study, we adopt the framework and technology of waste and river water injection as guidelines (Cao et al. 2022; Liu et al. 2021a; Sendros et al. 2020; Spellman et al. 2022), and the Ordovician aquifer was selected as the

✉ Ge Chen
cg5@cumt.edu.cn

✉ Yajun Sun
syj@cumt.edu.cn

1 School of Resources and Geosciences, China University of Mining and Technology, Xuzhou 221116, Jiangsu, People's Republic of China

2 Shandong Energy Group Co., Ltd., Jinan 250101, Shandong, People's Republic of China

3 Shandong Provincial Lunan Geology and Exploration Institute (Shandong Provincial Bureau of Geology and Mineral Resources No. 2 Geological Brigade), Jining 272100, Shandong, People's Republic of China

4 Shandong Engineering Research Center of Geothermal Energy Exploration and Development, Jining 272100, Shandong, People's Republic of China

5 Fundamental Research Laboratory for Mine Water Hazards Prevention and Controlling Technology, Xuzhou 221006, Jiangsu, People's Republic of China

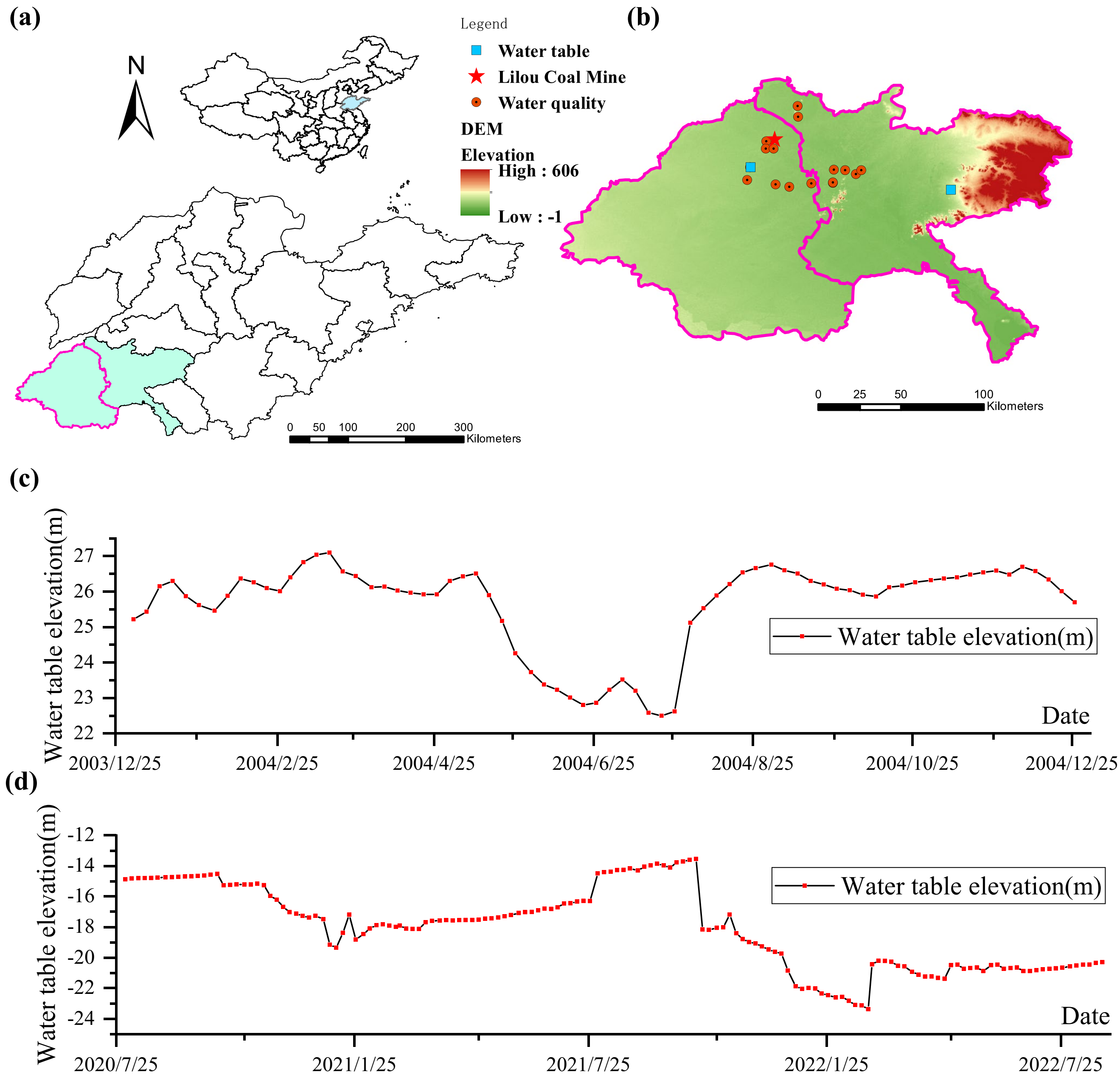

Fig. 1 Location of the study coal area and Ordovician aquifer water table and water quality monitoring points; **a** the geographical location of Shandong in China; **b** the location of the Lilou Coal Mine and distribution of Ordovician aquifer observation wells; **c** 1 year water level monitoring data of the Ordovician aquifer in 2004; **d** long-term water level monitoring data of the Ordovician aquifer from 2020 to 2022

targeted recharge aquifer. Ordovician limestone water has been used as a source of geothermal energy and for industrial consumption, and the Ordovician water level in the study area has decreased by 15–30 m over the past 20 years. As shown in Fig. 1c, d, replenishment of Ordovician water resources by artificial injection could mitigate or even reverse this water level decline. Various case studies (previously published articles) have involved water injection for different purposes, mainly focusing on oil and gas exploitation, geothermal injection, artificial recharge to compensate for groundwater overexploitation, coalbed methane extraction, CO_2 geological storage, and mitigation of seawater intrusion (Cai et al. 2023; Li et al. 2023; Lu et al. 2017; Pu et al. 2021; Shi et al. 2022; Wang et al. 2022). There have been few studies targeting mine water injection worldwide (Al-Shalabi and Sepehrnoori 2016). The Wutongzhuang

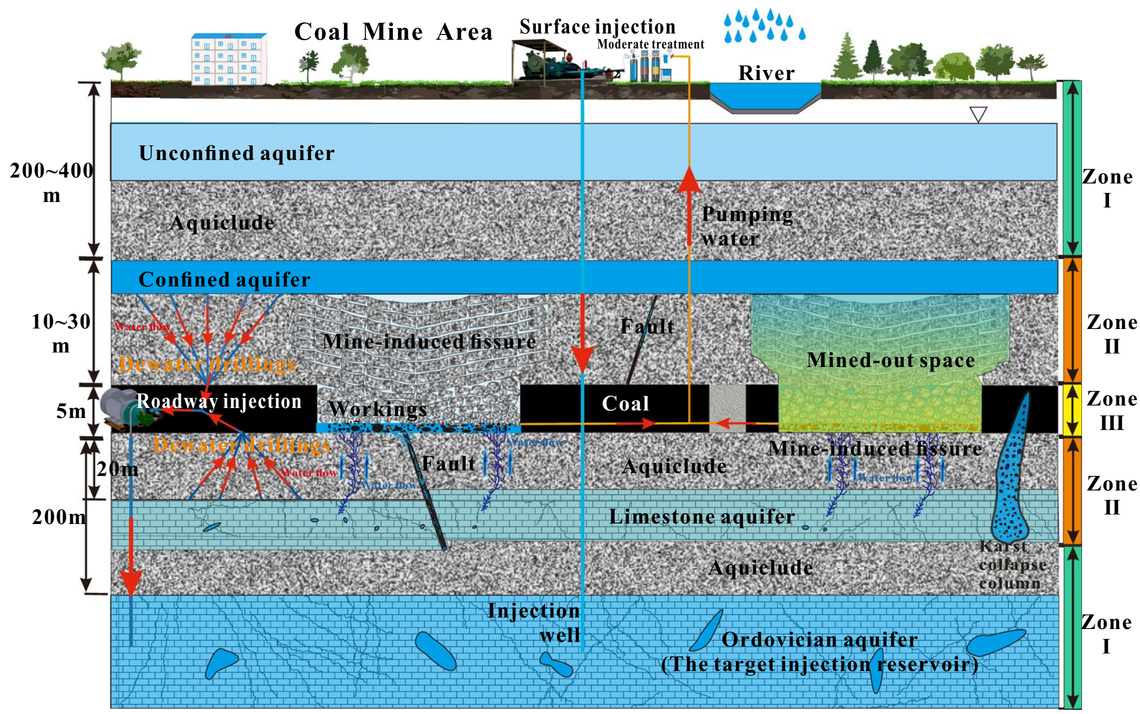

Fig. 2 Hydrogeological characteristics and water quality three-zone conceptual model for the Lilou Coal Mine. Mine water injection includes surface injection and underground roadway injection. Surface injection indicates that mine water with coal cinder drainage from workings is injected after pretreatment. Roadway injection suggests that water from the coal roof and floor aquifers is directly injected into the Ordovician limestone aquifer. The red arrow indicates the direction of water flow

Coal Mine, Zhongguan Iron Mine, and some coal mines in the Mu Us Desert in China have been investigated with regard to relevant applications (Chen et al. 2022). Mine water injection not only reduces SCMW discharge into the surface environment and ecological pollution of shallowly buried aquifers but also reduces water resource waste and costly water treatment.

Article 43 of the People's Republic of China Water Pollution Prevention Law states that *artificial recharge shall not worsen the targeted aquifer's water quality*. Thus, it is necessary to ensure that the injected mine water has a better water quality than the Ordovician aquifer to achieve the final objectives of effectively replenishing and protecting groundwater resources (Alqahtani et al. 2021; Khadra and Stuyfzand 2020; Lu et al. 2017). In the mine water injection pilot test at the Lilou Coal Mine, only the Na^+ concentrations in the mine water exceeded that in the water of the deeply buried Ordovician aquifer (Table 2). Otherwise, the mine water quality is generally better than that of the targeted Ordovician aquifer water, which suggests that the SCMW in the Lilou Mine is suitable for injection after moderate Na^+ treatment. This would greatly reduce the need for complex advanced SCMW treatment processes and effectively alleviate the difficulty of groundwater resource management for the coal mines.

Surface advanced treatment technology has typically been used for mine water treatment purposes in north China's coal mining areas, and the cost of building such a water treatment plant usually exceeds $20 million (U.S.). As a novel in situ mine water treatment technology, mine water injection in this area would provide the following benefits: (1) It would ensure that SCMW injection does not cause environmental pollution (the ion concentration in mine water is either less than the Ordovician aquifer or the Class III water standard); (2) The Ordovician aquifer would be recharged to maintain its water level; (3) Mine water treatment expenditures would be greatly reduced; (4) The economic pressure of coal enterprises would be relieved, demonstration projects can be established, and a foundation would be laid for the more general use of this process. In this study, the feasibility and field application of mine water injection in coal mining areas was evaluated. This can provide an example for mine water injection in similar hydrogeological conditions and can aid the development and reuse of mine water.

Study Area

Ordovician Aquifer Water Table Drawdown Trend

In this study, we chose Shandong Province as a typical geological portion of northern China; its geographical location in China is shown in Fig. 1a. The main sedimentation strata are Permian (P), Carbonic (C), and Ordovician (O) strata, and the surface elevation fluctuates very little in the Lilou Coal Mine area, as shown in Fig. 1b (the location is marked with a red star). The Ordovician aquifer contains abundant groundwater due to the well-developed karst fractures and cave sections but is deeply buried (Fig. 3b). The Ordovician aquifer is influenced by many artificial pumping wells, including wells for geothermal exploitation (water temperature range: 50–60 °C) and by hydraulic connection with upper limestone aquifers by faults and karst column collapses (Kang et al. 2023; Wang et al. 2015; Zeng et al. 2023; Zhang and Wang 2021). The Ordovician aquifer water level has continuously declined since 2000, according to monitoring data of two long-term observation wells (their location is marked with a blue box in Fig. 1b). The Ordovician aquifer fluctuation trend in 2004 is shown in Fig. 1c, and the average water table elevation is 25.6 m above sea level. The average water level elevation was − 18 m from 2020 to 2022, and the fluctuation trend is shown in Fig. 1d. The results suggested that the Ordovician water level decreased by 2.7–3.8 m/year in the study region, and the drawdown rate was greater during the geothermal exploitation period from November to March in recent years, as shown in Fig. 1d.

Ordovician Limestone Aquifer Recharge Schemes

The mine water inrush sources in the Lilou Coal Mine are sandstone aquifers above the mine (accounting for 70% of the total mine water quantity) and limestone aquifers below the coal floor (accounting for 30% of the total mine water quantity). A 2D conceptual geological tectonic model is shown in Fig. 2. Mining activities are the main driving force for the evolution of the mine water quality, mainly including disturbance in mine-induced failure zones, water-conducting faults, karst collapse columns, and water-conducting boreholes. Due to the hydraulic connectivity between aquifers and coal seam, the mine water quality greatly varied during mining compared to before mining. Groundwater flows into the mine workings and roadways, forming SCMW. Based on the vertical disturbance fracture zone ranges during mining activities, the characteristics of the ground water quality in the Lilou Coal Mine can be generalized as having three zones (Sun et al. 2022), namely, Zones I, II, and III (the fracture zone extends into the aquifer), as shown in Fig. 2.

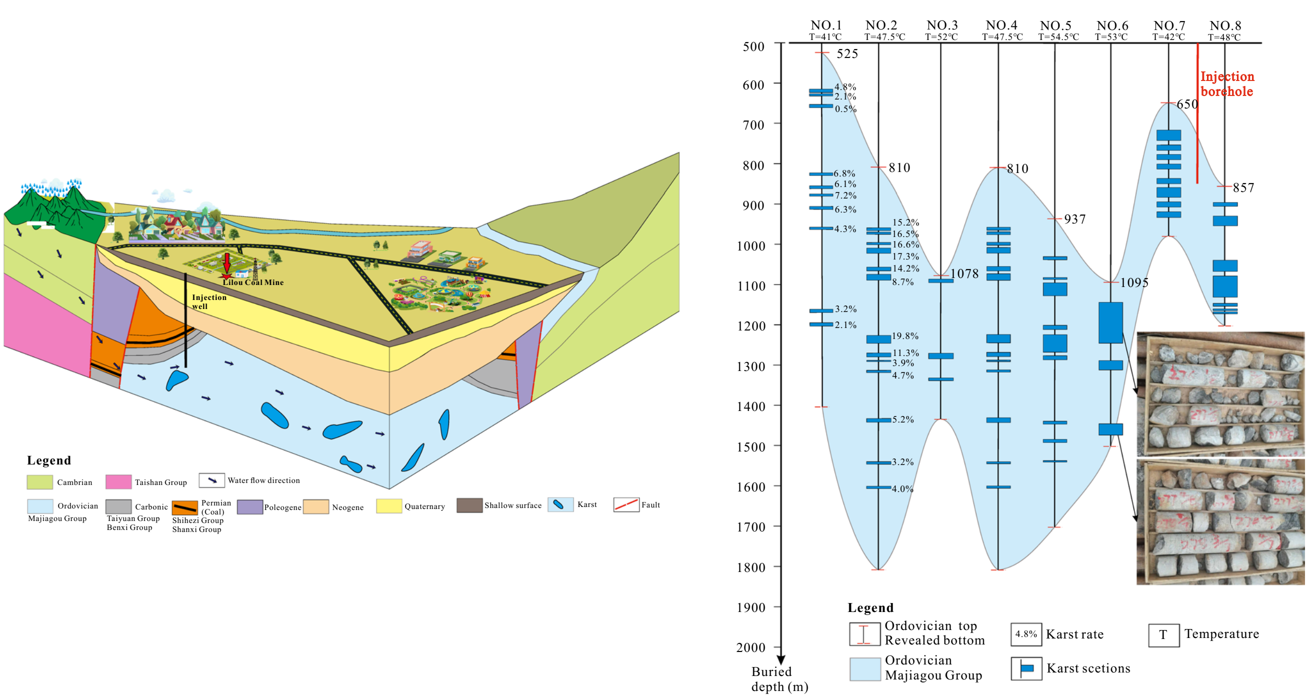

Fig. 3 Ordovician limestone water richness characteristics in the study area; **a** 3D tectonic unit of the Lilou Coal Mine and the injection well location, revised from Kang et al. (2023); **b** in situ drilling rock core reveal the karst development scale and burial depth of the Ordovician aquifer in the region, as well as fractured rock core samples, revised based on Kang et al. (2023)

Zone I: The range outside of the mine-induced failure zones. The water-bearing aquiclude medium and surrounding rock are not affected by the mining, and groundwater does not participate in the formation of the SCMW, such as shallowly buried unconfined aquifers and deeply buried Ordovician aquifers.

Zone II: The range in the mine-induced fissure zones and outside of the mine workings and roadways. Groundwater can enter roadways and workings along preferential seepage fracture channels, as shown in Fig. 2. Short-term water mixing and water–rock (water-coal) interactions may occur in this process, resulting in slight changes in the mixed mine water source quality characteristics before inrush into the mine workings and roadways (Mugova and Wolkersdorfer 2022).

Zone III: The mine workings and roadway void space. This zone is the most affected by human activities. The mine water quality changes after long-term water physical mixing, water–rock (water-coal) chemical interactions, and microbial interactions during the mining period, during which most of the SCMW is produced (Yajun et al. 2021).

Due to the high expenditure of annual mine water treatment and coal mine drainage in the Lilou Mine, more than $23.2 million (U.S.) has been spent to build large-scale water treatment plants at the surface; the average water treatment cost ranges from $2.0–2.1 (U.S.) per tonne at present. In this study, we propose that the water resources of Zones II and III (shown in Fig. 2) can be injected into the deep Ordovician aquifer in Zone I, which does not eliminate the threat to mining safety but protects groundwater resources to some degree (Zeng et al. 2023). The deeply buried Ordovician aquifer in Zone I should be prioritized as the targeted injection reservoir because of its high water table drawdown trend. Aquifer recharge should meet the following basic principles: (1) There should be no additional threat of mine water inrush accidents. (2) Regional ground water flow circulation should not be negatively affected. (3) The Ordovician aquifer should be effectively replenished. (4) The mine water quality is generally better than that of the Ordovician aquifer water, and no pollutants exist or are produced.

According to the requirements of mine water inrush disaster prevention, mine water surface drainage reduction, and large-scale water treatment (Li et al. 2020b), the Lilou Mine's groundwater resources can be divided into two water types: mine water source aquifers (confined aquifer water resources, mainly occurring in Zone II) and working mine water (i.e. SCMW, mainly occurring in Zone III). The water quality in Zone II reflects the characteristics of the mine water inrush source aquifers, which can be directly injected without treatment after collection from dewatering boreholes in coal (rock) roadways (Fig. 2). Roadway injection not only facilitates the prevention of water inrush disasters but also effectively reduces mine water production (Zeng et al. 2023).

Method

Reservoir Characteristics

Ordovician limestone aquifers with dense and hard carbonate rocks comprise a suite of shallow marine sediments that are thickly layered and widely distributed in the study area. The karst process facilitated sedimentation and filling, producing an average porosity of ≈ 3% in the intact carbonate rocks. Because the study area is located near several large-scale faults, small secondary fault structures are well developed in the Lilou Mine, as shown in Figs. 3a and 5a, but most do not conduct water. The Ordovician aquifer has undergone intense geological movement, weathering, and repeated dissolution, and there are many fractured karst sections with well-developed fissures and caves (Kang et al. 2023). The statistics for eight drilling rock cores of the Ordovician aquifer are shown in Fig. 3b (Kang et al. 2023), and the karst fracture rate ranges from 6 to 14%.

Limestone fissures and karst caves are important for water circulation and injection storage (Spellman et al. 2022), and the aquifer geo-temperature is relatively high. The temperature data of eight boreholes (Fig. 3b) shows that the reservoir can be used for geothermal exploitation. The average thickness of the karst development section accounts for 9.7–65.0% of the total Ordovician aquifer thickness, with an average of 37.2%. The karst development rate was 0.5–17.3%, with an average of 7.4%. The average thickness of the karst fracture development section was 140 m, the aperture rate in the karst fracture development section ranged from 3.4 to 10.4%, with an average of 6%, and the permeability ranged from 0.1 to 6.7 (10^{-3} μm^2), with an average of 1.8 (10^{-3} μm^2). The characteristics of the karst development sections usually provide sufficient water storage space for mine water injection (Spellman et al. 2022).

In Situ Hydrogeological Tests

Due to the thickness of the Ordovician aquifer, the bottom of the strata has not yet been completely exposed by drilling, so both the injection and observation wells were designed as incomplete wells (Li et al. 2020a; van Lopik et al. 2020). Based on the topography and geographical location of the Lilou Mine area, the injection well was drilled in the coal industrial square, and the observation well was drilled in an underground coalbed roadway. The burial depth of the Ordovician aquifer was relatively small in the industrial square relative to other areas, so the drilling cost was less than that of other schemes. Also, the industrial square was located close to the water treatment plants, which made the location more convenient for injection equipment transportation and mine water pipe line distribution.

The hydrogeological parameters were obtained by analyzing the experimental data of 12 geothermal injection and pumping cycles (Table 1), and the permeability of the Ordovician aquifer was obtained before the SCMW injection and numerical simulations. These hydrogeological tests were conducted in the same incomplete well, with a burial depth ranging from 1058 to 1313 m, and the filter screen length and borehole diameter were 250 m and 177 mm, respectively. Because the hydrogeological tests involved both pumping and injection tests in a single incomplete well, the permeability coefficient (K) of the Ordovician aquifer can be calculated according to Babushkin's model (Babuskin et al. 1975), which can be expressed as:

$$Q = \frac{2 \times \pi \times K \times L \times S_w}{\ln\left(\frac{1.32 \times L}{r_w}\right)} \tag{1}$$

where: Q is the water injection and pumping flow rate of the incomplete well (m/d); K is the permeability coefficient (m/d); L is the filter screen length of the incomplete well (m); S_w is the water table drawdown at the center of the incomplete well (m); and r_w is the radius of the incomplete well (m).

The permeability coefficient (K) in the 12 pumping and injection tests was obtained with Eq. (1), as listed in Table 1. To eliminate the error of these 12 hydrogeological tests, after removing the maximum and minimum calculated permeability coefficient values, the remaining K values were averaged, and the final average permeability coefficient of the Ordovician aquifer was 1.3 m/d.

Hydrogeological pumping tests were also conducted in a complete well near the outcrop area to further verify the accuracy of the calculated permeability coefficient (K); the location of the pumping well is shown in Fig. 5a (OB1, the location is marked with a green circle). This borehole completely penetrated the Ordovician aquifer from top to bottom, and the length of the filter screen was equal to the aquifer thickness at this location, at 55.0 m. Three pumping tests were conducted in this complete well, and the pumping processes and water level fluctuation trend are shown in supplemental Fig. S-1. According to the model of steady and complete well flow of confined water, Eqs. (2) and (3) can be expressed as:

$$K = \frac{0.366 \times Q}{S_w \times M} \times \lg\left(\frac{R}{r_w}\right) \tag{2}$$

$$R = 10 \times S_w \times \sqrt{K} \tag{3}$$

where Q is the water injection and pumping flow rate of the complete well (m/d); K is the permeability coefficient (m/d); M is the aquifer thickness, equal to the filter screen length (m); R is the hydraulic influence radius (m); S_w is the water table drawdown at the center of the complete well (m); and r_w is the radius of the complete well (m).

Substituting the relevant parameters into Eqs. (2) and (3), the permeability coefficients during steady flow of in the three pumping tests were 1.263, 1.528, and 1.925 m/d, with an average of 1.6 m/d. The results are generally consistent with the calculated results of the above mentioned incomplete well (1.3 m/d), which verifies the accuracy of the permeability coefficient K results obtained in the 12 incomplete well hydrogeological tests. Moreover, the results show that the Ordovician aquifer exhibits strong hydrodynamic

Table 1 Statistical data of the injection and pumping tests in the penetrating well of the Ordovician aquifer

Type	Times	Duration (h)	Stabilization time (h)	Q (m^3/h)	Water quantity (m^3)	Water table (m)	S_w (m)	K (m/d)
Injection	1	97	26	65.2	6321	25.3	+7.4	1.1
	2	120	24	78.3	9192	28.9	+11.1	0.9
	3	96	25	48.4	4642	21.5	+3.7	1.7
	4	95	53	60.5	5738	20.2	+2.3	3.3
	5	119	55	76.4	9076.2	24.8	+7.0	1.4
	6	240	168	81.5	19,555.3	27.2	+9.3	1.1
Pumping	1	97	46	65.2	6327	11.0	−7.3	1.1
	2	120	33	78.7	9246	9.2	−9.1	1.1
	3	96	36	48.5	4657	13.5	−4.8	1.3
	4	95	47	41.7	4035	14.4	−4.0	1.3
	5	119	76	53.3	6345	13.4	−5.0	1.3
	6	240	87	57.4	13,814	13.0	−5.4	1.3

S_w (m) column, "+" indicates water level rise, "−" indicates water level drawdown, and the average surface elevation is 43 m

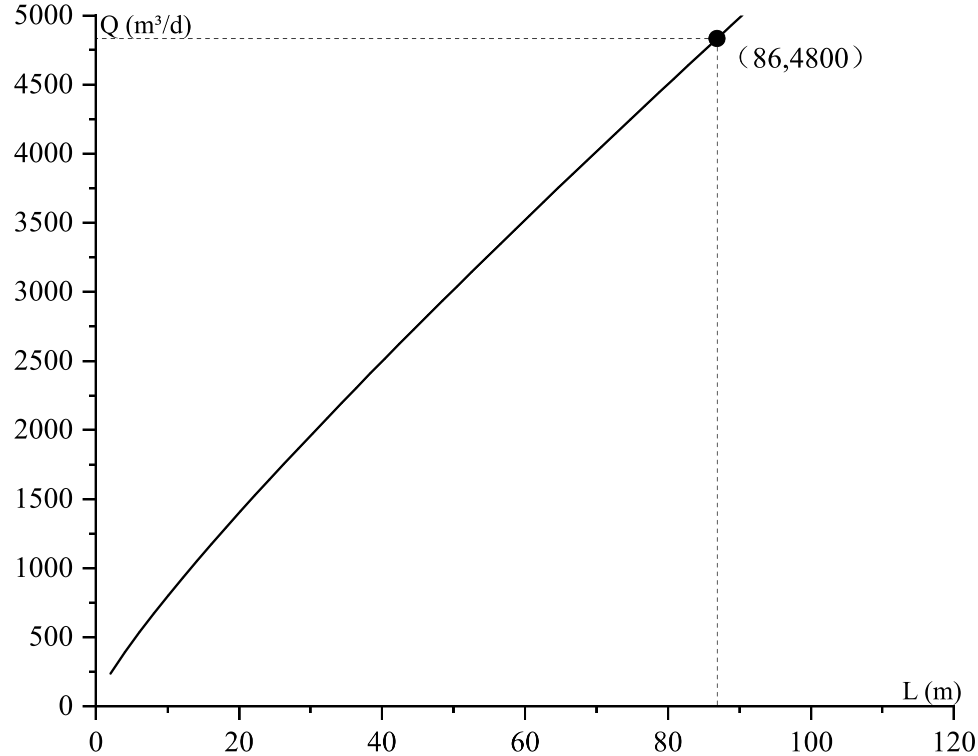

Fig. 4 Standard curve of the relationship between the injection flow (Q) and filter screen length (L) for $S_W = 50$ m

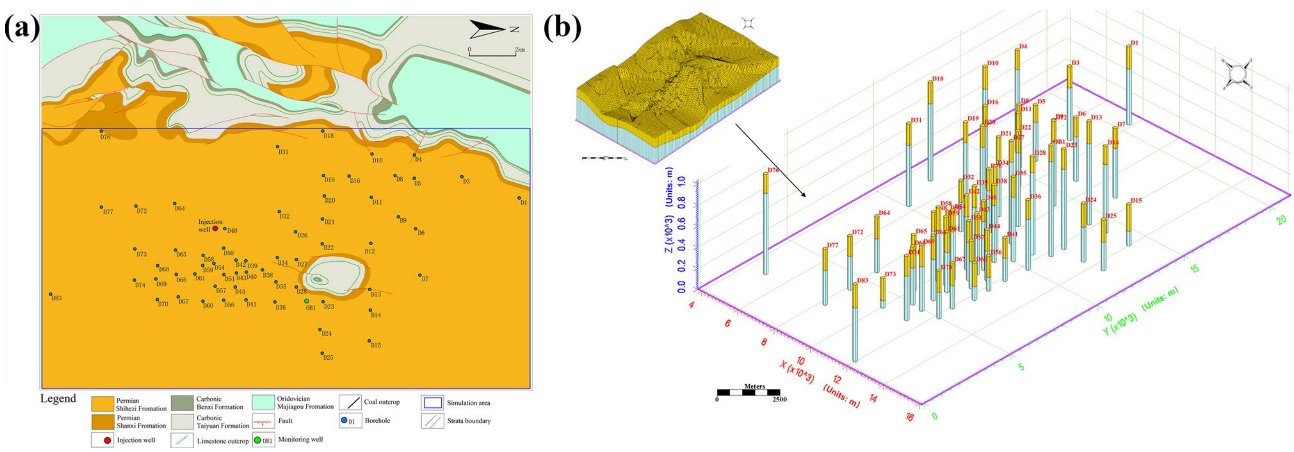

Fig. 5 Borehole distribution and conceptual model of the Ordovician aquifer; **a** geological region of the simulation model and the distribution of 64 geological boreholes; **b** 3D view of the conceptual model of the Ordovician aquifer and boreholes

conditions, which are very conducive to the rapid dissipation of the reverse cone of water depression during injection.

Filter Screen Length of the Injection Well

At present, the mine water inrush flow rate in the Lilou Mine is 570 m^3/h, and the above mentioned tests demonstrated that the Ordovician aquifer could serve as the targeted injection formation. The designed single-well mine water injection rate was 200 m^3/h, which would allow an annual injection quantity of ≈1.8 million m^3. According to the water quality comparison, karst fracture development degree, reservoir potential water storage spaces, and Ordovician aquifer permeability coefficient (K), and assuming that the Na^+ concentrations can be decreased to less than 319 mg/L, the SCMW in the Lilou Mine can be recharged into the Ordovician aquifer to mitigate the continuous drawdown in its water level.

The Ordovician aquifer exhibits high permeability, well-developed karst fractures, and highly favorable water flow conditions that will further reduce the cost of recharge and avoid the negative effects of high-water pressure injection, such as high pressure-induced seismic activity (Sun et al. 2017; Zhao et al. 2018). The plan is to adopt the principle of zero pressure injection, which refers to maintaining the water pressure at the ground surface at zero throughout the injection process, so that the water automatically flows into the Ordovician aquifer. This will avoid fracturing of the Ordovician reservoir by high-pressure injection and allows us to ignore spatio-temporal changes in the permeability due to hydraulic fracturing. Based on the buried depth of the Ordovician aquifer in the Lilou Mine, the average buried depth of the confined water table is ≈ 50 m, and so the maximum rise in the water level during injection can be set to 50 m. The functional relationship between the injection flow (Q) and filter screen length (L) based on Eq. (1) can be expressed as Eq. (4), given that the water table drawdown, $S_W = 50$ m.

$$Q = \frac{398.78 \times L}{\ln(14.92 \times L)} \quad (4)$$

Figure 4 shows that the filter screen length (L) of the injection well drilled into the Ordovician aquifer must be at least 86 m to provide an injection rate of 200 m^3/h (i.e. 4800 m^3/d). To ensure the quantity of SCMW injection, the length of the drilling filter was set to 150 m, which is much larger than the theoretical calculation value of 86 m. If the borehole enters the aquifer at 150 m (equal to the filter length) and the surface water pressure is 0 in the injection well, the theoretical maximum injection rate should be 7755 m^3/d, which is much more than the required injection rate of 4800 m^3/d. At a settled flow rate of 4800 m^3/d, the water level in the injection well should only rise 30 m, the maximum confined water table buried depth will be 20 m below the surface, and the injection hydraulic influence radius (R) must be slightly less.

Numerical Simulation Conceptual Model

Mine water injection will artificially change the local Ordovician aquifer water circulation, increasing the hydraulic gradient, velocity, pore water pressure and water table near the injection well, and forming a reverse cone of depression water table morphology in the Lilou Mine. Numerical simulation methods can be used to predict water table rebounding of the Ordovician aquifer by single-well injection (Cognac and Ronayne 2020; Sanayei et al. 2021; Wang et al. 2012; Zhang et al. 2017b), revealing the temporal and spatial evolution principles of the hydrodynamic field after recharging. This can also provide evidence for Na^+ migration and diffusion and mining safety evaluation. According to the drilling data of 64 boreholes in Lilou Mine (including the abovementioned complete well, OB1), as shown in Fig. 5a, the average buried depth of the Ordovician aquifer roof was 1080 m. Because the Ordovician aquifer was not completely exposed, the bottom elevation was artificially set at -1500 m, and the buried depth was 1543 m in the numerical model (the average ground surface elevation was 43 m), as shown in Fig. 5b. The numerical model was divided via the use of the finite element method; the 2D simulation range is shown as the blue frame box in Fig. 5a. To facilitate the numerical model calculation, the numerical model was divided into two layers: and the strata between the Ordovician roof and the coalbed as the first layer, the targeted portion of the Ordovician aquifer as the second and bottom layer. Each cell box represents an actual distance of 50 m, as shown in Fig. 6.

Results

Numerically relevant parameters such as buried depth, thickness, porosity, initial water table, permeability coefficient, heterogeneity, and monitoring data of the Ordovician aquifer water level were substituted into the model. Because the hydraulic influence radius (R) of single-well injection cannot be extended beyond the boundary, the peripheral boundaries of the model were mainly defined as a constant water table, and the numerical model was run under an injection flow rate of 4800 m^3/d.

Figure 6 shows the evolution of the water table near the injection well at a continuous injection flow rate of 4800 m^3/d. After 10 days, the hydraulic influence radius (R) of injection was 145 m (Fig. 6a); after 6 months, it was 810 m (Fig. 6b); after 18 months of water injection, it was 1020 m (Fig. 6c); and after 3.5 years, it was 1480 m (Fig. 6d). The injection simulation revealed that the hydraulic influence radius of injection does not exceed the numerical model's boundary.

The numerical simulation results in Fig. 6 show that the water level obviously rose during the recharge process, but that it never exceeds the ground surface, which meets the requirements of zero pressure in the injection well at the surface. The hydraulic influence radius (R) gradually increases and the maximum influence radius reaches 1480 m after 3.5 years during injection.

Discussion

Water Quality Injection Preconditions

Water Quality Comparison of the Lilou Mine

The Lilou Mine was selected for the injection pilot; its geographical location in Shandong is shown in Fig. 1b (the location is marked with a red star). We collected mine water

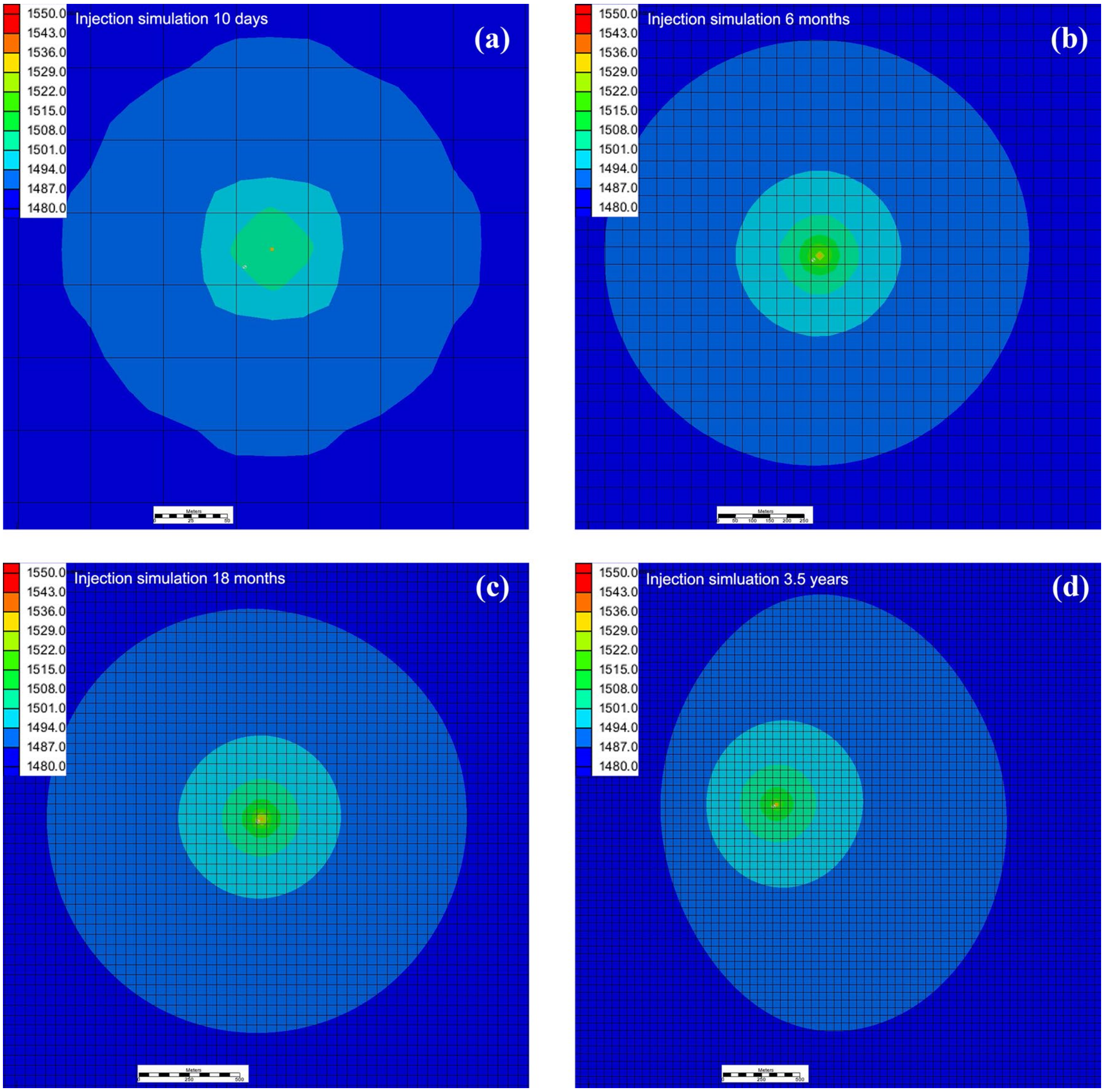

Fig. 6 Water level rise results after different model simulation periods; **a** water level rise at 10 days during injection; **b** water level rise at 6 months during injection; **c** water level rise at 18 months during injection; **d** water level rise at 3.5 years during injection. Each cell box represents an actual distance of 50 m

samples and Ordovician limestone aquifer water samples and analyzed the water samples using Varian ICP-OES 720 and Methohm 881 Compact IC pro equipment. The water quality of the sampled SCMW and Ordovician aquifer water were compared. In this study, we analyzed 27 water quality components, as shown in Table 2.

The precondition of SCMW injection required that either the ion concentration be less than the Class III water standard level, or that the ion concentration be less than the Ordovician aquifer's groundwater. The comparison demonstrated that the Na^+ concentration in the SCMW (855.5 mg/L) exceeded that in the Ordovician aquifer water (319.7 mg/L) and would have to be pretreated before injection. The other factors components were mainly less than in the Ordovician limestone water (except for HCO_3^-, NO_3^{-N}, NO_2^{-N}, and pH, but these were all less than the Class III water standard), which suggests that the SCMW quality of the Lilou Mine is generally better than that of the targeted Ordovician aquifer. Moreover, most of the ion indicators in the SCMW did not exceed the Class III groundwater standard (except for sulfate and TDS, but these were both less than in the Ordovician aquifer water). This provided a favorable precondition for water injection engineering implementation and indicated that the SCMW can be injected after moderate water treatment (to lower the Na^+ concentration).

Table 2 Water quality comparison details between SCMW and Ordovician aquifer water in the Lilou Coal Mine (unit: mg/L)

Items	Mine water	Ordovician aquifer water	Class III	Items	Mine water	Ordovician aquifer	Class III
K^+	8.27	28.4		NO_2-N	0.05	< 0.003	≤ 1
Na^+	855.5	319.7	≤ 200	Total hardness	141.2	1902.3	≤ 450
Ca^{2+}	42.2	569.7		pH	8.3	7.44	6.5–8.5
Mg^{2+}	8.7	116.5		Free CO_2	0	12.4	
NH_4^+-N	0.5	1.6	≤ 0.5	Erosion CO_2	–	0	
Fe^{3+}	0.2	0.3	≤ 0.3	H_2SiO_3	23.8	25.3	
Fe^{2+}	0	0		H_2S	–	< 0.02	
Cl^-	151.6	320.8	≤ 250	TDS	2945.6	3544.2	≤ 1000
SO_4^{2-}	1521	1986.9	≤ 250	As	–	< 0.001	
HCO_3^-	323	170.5		Hg	–	0.0003	
CO_3^{2-}	0	0		Cr (VI)	–	–	
PO_4^{3-}	0.08	< 0.07		Volatile phenol	–	< 0.002	
F^-	1	3.2	≤ 1.0	Cyanide	–	< 0.002	
NO_3-N	2.1	0.095	≤ 20				

TDS—total dissolved solids; Class I—the best water quality type, Class V—the worst water quality type in GB/T 14848—2017 (Groundwater Quality Standard of China)

Multiwell Injection Feasibility

Although single-well recharge could facilitate the replenishment of groundwater resources in a certain area, the Ordovician aquifer is thick and widely distributed, and single-well injection only slightly influenced the regional hydrodynamic field. Coal mines with a better mine water quality in Shandong should be selected, and large-scale, multiwell injection should be conducted to achieve a greater water level rebound in the regional Ordovician aquifer (Manglik and Rai 2015; Zhang et al. 2017a). The popularization and application of this new in situ water injection technology can be realized by deep injection and by regionally raising the overall water level in the Ordovician aquifer.

At present, there are 24 coalfields in Shandong Province. After simple treatment, these water resources can be developed and utilized. To further clarify the water quality characteristics of Zone III in the Shandong coal mining area, we investigated and analyzed the mine water quality samples of select mines in 24 coalfields, combined with historical data of the hydrochemistry, hydrochemical analysis, literature data, and other collected materials; the results are summarized in supplemental Table S-1.

To thoroughly study the influence of mine water reinjection on the target layer, data from 16 Ordovician water quality monitoring boreholes in the study area (the location marked with a purple circle in Fig. 1b) and regional Ordovician limestone water quality data were obtained, as shown in supplemental Table S-2.

To compare the mine water quality and Ordovician limestone water quality more intuitively, we generated a box diagram, including parameters such as upper edge, upper quartile, median, lower quartile, lower edge, and potential error value (Fig. 7). The mine water and Ordovician aquifer water quality comparison revealed that the conventional components in both water types basically exhibited the same ranges, including $K^+ + Na^+$, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, TDS, and pH, and the concentrations of each component in both water types overlapped in a certain range, and the overall difference was small. The results are shown in Fig. 7.

Saline Coal Mine Water Treatment Technologies

It was necessary to reduce the Na^+ concentration in the mine water below that in the Ordovician aquifer water before injection. At present, the commonly used technologies for SCMW desalination include distillation, ion exchange, and membrane separation. Distillation is mostly suitable for water with salt concentrations greater than 4 g/L, while ion exchange is suitable for water with salt concentrations less than 500 mg/L (Sun et al. 2020). In contrast, membrane separation methods are more suitable for large-scale SCMW desalination, especially reverse osmosis (RO) (Mitko and Turek 2021; Xiong et al. 2017). Some integrated membrane systems can concentrate brackish mine waters, recovering more than 80% of the volume of mine water and producing dischargeable treated water. (Thiruvenkatachari et al. 2016). However, RO membrane separation technologies also have certain problems, such as high pretreatment requirements, easy blockage (short intervals between cleaning), corrosion of equipment, low multiples for concentration, and

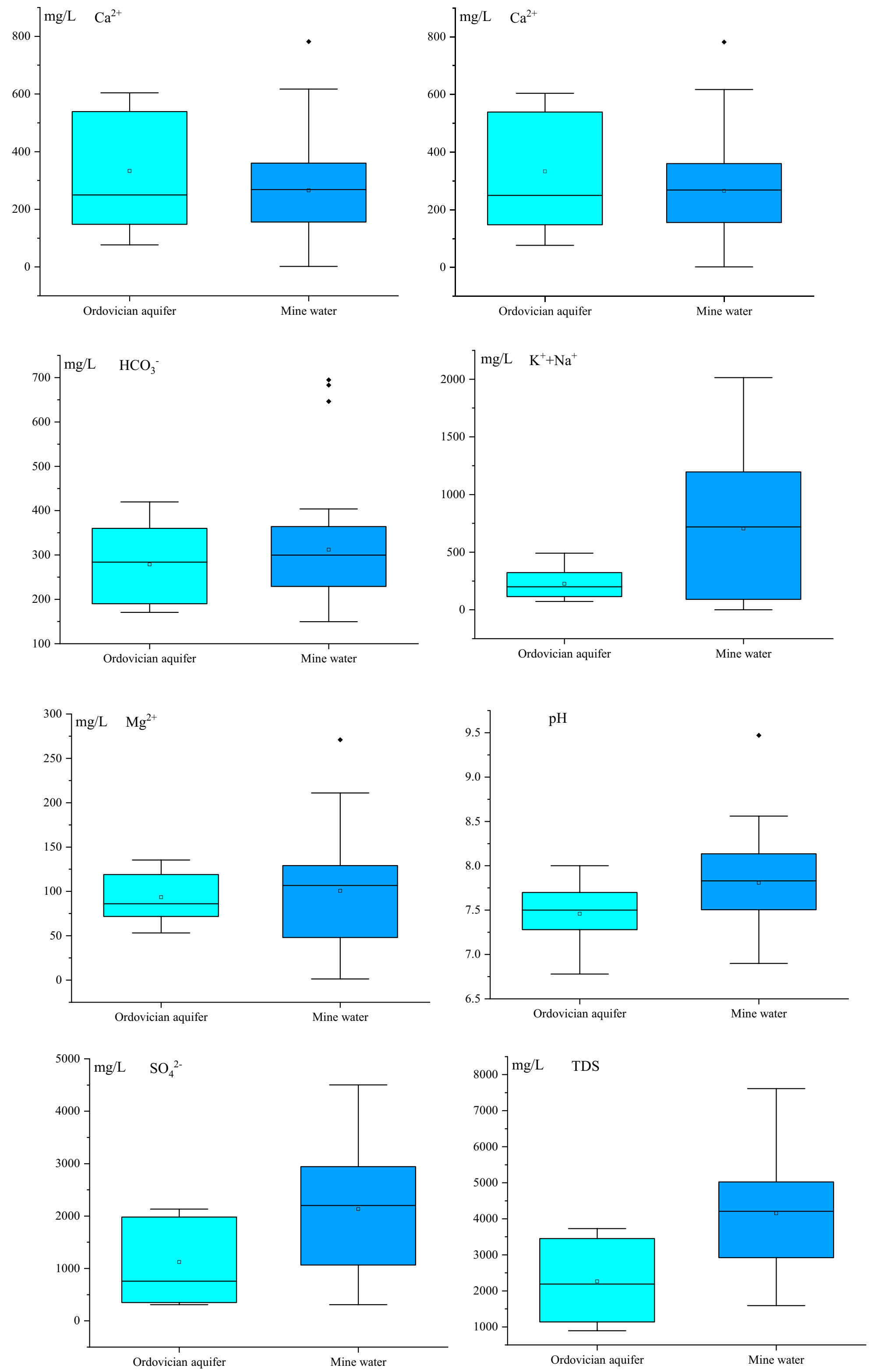

Fig. 7 Water quality comparison of conventional ion components between the Ordovician aquifer water and mine water

concentrated water treatment after RO application. When the salt concentration in mine water exceeds 6000 mg/L, it can impose a notable negative influence on the desalination rate, and the treatment cost of concentrated RO-treated wastewater is high, accounting for almost 30% of the total cost of RO desalination processes. In recent years, there have been great breakthroughs in the research of new materials and technologies for saline water desalination, such as electrochemical desalination, photothermal desalination, and graphene desalination (Chen et al. 2021; Gong et al. 2021; Liu et al. 2021b; Pinto et al. 2016), which could reduce the cost of mine water desalination. However, these studies are mainly still at the small-scale application and laboratory experimental stages and cannot yet be applied to large-scale mine water desalination.

The existing desalination treatment of SCMW in the mine area is integrated membrane concentration technology, and its treatment modules include six distinct modules (three pretreatment and three concentration treatment modules), which can be used to comprehensively achieve ultrafiltration, reverse osmosis, microfiltration, electrodialysis, and other processes (Fig. 8). The functions and effects of each module are listed in supplemental Table S-3.

Since the main goal was to decrease the Na^+ in the mine water to less than 319 mg/L, only the primary pretreatment, secondary pretreatment, and secondary concentration modules are needed, reducing SCMW treatment costs by at least 50%. Injection after moderate SCMW treatment saves 50% of the water treatment expenditure relative to discharging the treated water at the surface, which costs \$2 (U.S.) per m^3). In addition, \$ 0.3 (U.S.) per m^3 was charged for discharging the treated water into surface rivers and streams, according to the local water resource tax law of Shandong Province. Thus, mine water injection would save \$1.4 (U.S.) per m^3 in total. At an injection rate of 200 m^3/h (4800 m^3/d), the annual injection quantity totals ≈ 1.8 million m^3, and the annual benefits should be ≈ \$2.4 million (U.S.). If the injection period of a single well is estimated as 20 years, this can save \$48.3 million (U.S.), which can almost pay for the costs of injecting mine water underground for the whole life cycle of coal mining.

Risk of Fault Leakage

The water-conducting fault structure mainly strengthens the hydraulic connection among aquifers, forming preferential flow channels. The faults in the Lilou Mine were largely normal faults, which exhibit a waterproof function and low water permeability. However, there are at least three faults within 1000 m near the injection well, as shown in Fig. 9a. Increasing the water pressure in the Ordovician aquifer decreases the effective stress, shear strength, and cohesion of fault structural planes (Zhao et al. 2018). Under the influence of coal mining and water level rise near the injection well, the faults can bear an increase in water pressure, as shown in Fig. 9b, and there is a risk that the water-resisting fault can be transformed into a water-conducting fault. If the injected water enters a water-resisting hydrogeological unit, the high-pressure mine water will affect the upper aquifer through the geological structure (faults) and could cause mine water inrush accidents (Li et al. 2020b; Zeng et al. 2023). When the water pressure exceeds the sum of

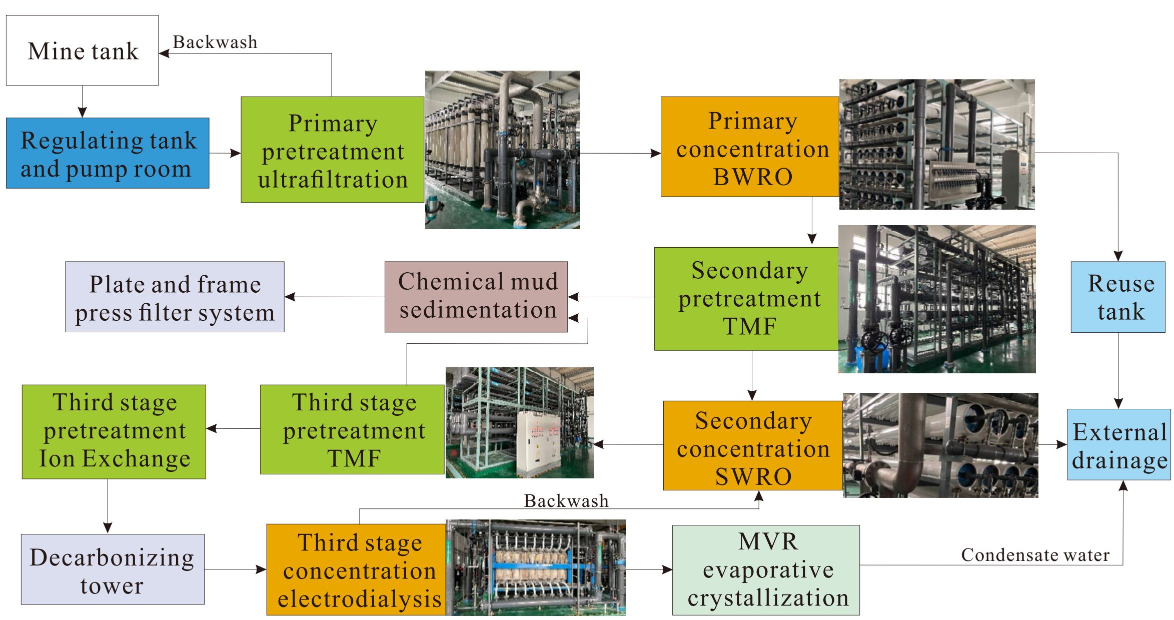

Fig. 8 Surface ground large-scale SCMW treatment plants and the existing large-scale SCMW membrane concentration treatment processes

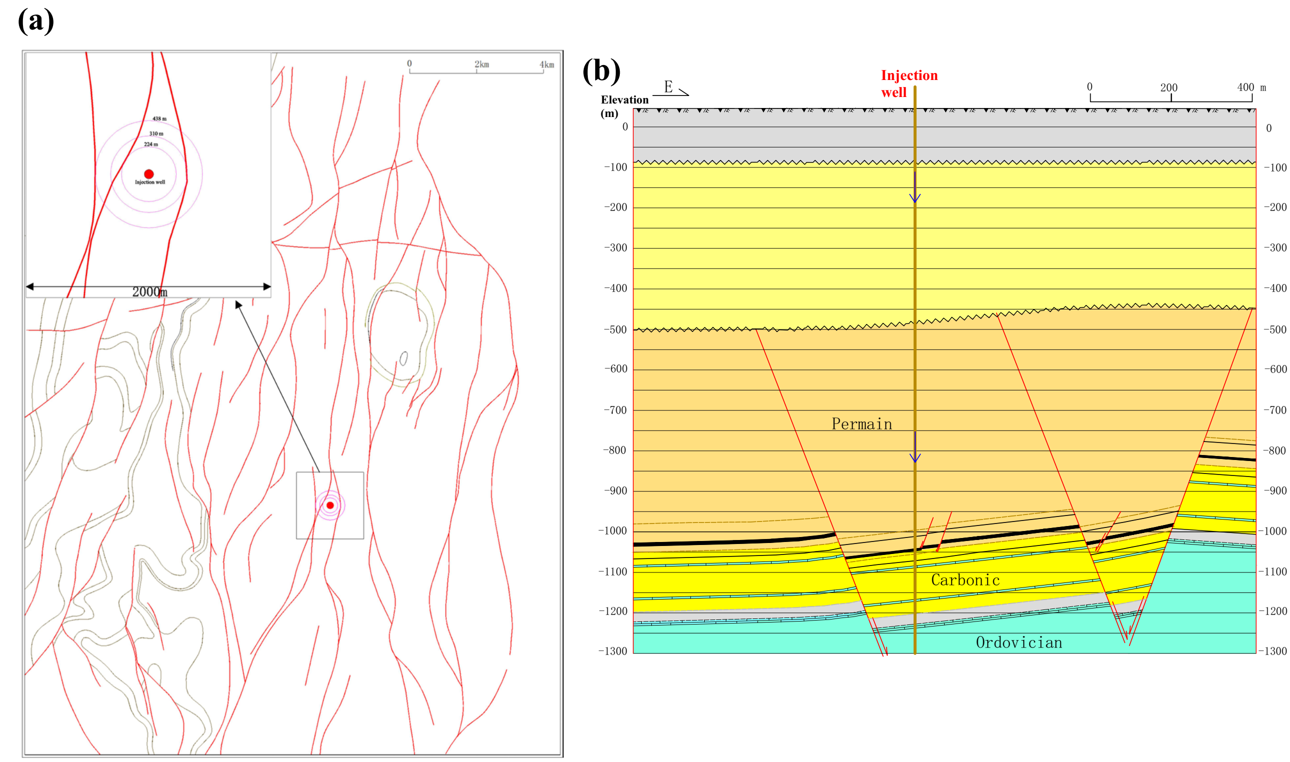

Fig. 9 Fault structure distribution in the Lilou Coal Mine and profile of faults adjacent to the injection well; **a** fault distribution in the study mine area; **b** the existing 3 normal faults profile near the water injection well

the minimum principal stress and the tensile strength of the rock, tensile cracks perpendicular to the direction of the minimum principal stress can appear. Several processes can trigger pore pressure increases in the faults, leading to fault failure, induced seismicity, and increased fault permeability (He et al. 2022; Zhao et al. 2018). A mathematical model to simulate fault activation during water injection was developed by Nguyen et al. (Nguyen et al. 2019) to assess the effects of in situ stress, fault shear strength parameters, and heterogeneity. It was shown that these factors were critical and must be adequately characterized to predict the hydro-mechanical behavior of faults (Nguyen et al. 2019). Therefore, it is very important to study water inrush accidents caused by fault activation, which is an important component of safety evaluation of mine water injection (Li et al. 2020b).

Long-term monitoring and an in situ in advance warning system should be established to prevent mine water inrush accidents after injection, so an Ordovician aquifer water pressure monitoring hole was drilled in the Lilou Mine underground roadway. According to the hydrogeological structure in the mine area, historical data of water inrush accidents, and similar water inrush data from adjacent mines, the key factors influencing water inrush in the study area were identified, including mining, a complex geological structure, fault structure reactivation, water sources, aquifer water pressure, mine water quality, and mine-induced fissure zone height/depth. (Cognac and Ronayne 2020; Fallatah et al. 2019).

Conclusions

Mine water injection is a new in situ technology for low-cost and large-scale SCMW treatment in China. Considering the Ordovician aquifer water level decline rate of 2.6 m/year, we proposed to recharge groundwater resources with moderately treated SCMW to greatly reduce the annual water treatment expenditures.

The deeply buried Ordovician aquifer was selected as the targeted recharge layer based on the four principles of water injection. It was concluded that the mine water quality of the Lilou Coal Mine was generally better than that of the Ordovician aquifer water after a comparison of 27 water quality factors. This provided a favorable precondition for water injection implementation and showed that SCMW can be injected after moderate treatment (to decrease the Na^+ concentration).

The Ordovician aquifer is a well-developed karst aquifer, with an average karst development section of 140 m, and a karst fracture rate ranging from 6 to 14%. Along the vertical direction, the average thickness of the karst development section accounts for 37.2% of the total thickness, and the average karst development rate is 7.4%. The average permeability coefficient of the Ordovician aquifer is 1.3 m/d, based on 12 injection and pumping hydrogeological tests in an incomplete well. These findings suggest that, in general, the Ordovician aquifer provides suitable seepage conditions and a high potential for water storage.

Adopting the Lilou Mine as the numerical simulation area, water injection could realize zero-pressure recharge and single-well recharge of 4800 m^3/d. The evolution of the hydrodynamic field under single-well recharge was examined, and the numerical simulation results were basically consistent with the theoretical calculation results. Under the premise of reducing Na^+ concentrations below 319 mg/L, the anticipated annual expenditure savings was ≈ \$2.4 million (U.S.) after greatly simplifying the existing desalination treatment processes.

However, single-well recharge will only slightly mitigate the decline of the regional Ordovician aquifer hydrodynamic field, and so further research involving multiwell injection must be performed to raise the regional water level. Many coal mines in Shandong with better water quality should be subjected to the popularization and application of water injection to achieve a meaningful water level rebound in the regional Ordovician aquifer.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10230-024-00977-3.

Acknowledgements This work was funded by the National Key Research and Development Project of China (Grant 2019YFC1805400), the Shandong Energy Group Co., Ltd Key, Science and Technology Project (Grant SNKJ2022A02-R18), the National Science Foundation of Jiangsu Province (Grant BK20210524), and the National Natural Science Foundation (Grant 42202268). We thank the editors and anonymous reviewers for their valuable suggestions.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

References

Alqahtani A, Sale T, Ronayne MJ, Hemenway C (2021) Demonstration of sustainable development of groundwater through aquifer storage and recovery (ASR). Water Resour Manag 35(2):429–445. https://doi.org/10.1007/s11269-020-02721-2

Al-Shalabi EW, Sepehrnoori K (2016) A comprehensive review of low salinity/engineered water injections and their applications in sandstone and carbonate rocks. J Pet Sci Eng 139:137–161. https://doi.org/10.1016/j.petrol.2015.11.027

Babushkin VD, Böcker T, Borevsky BV, Kovalewsky VS (1975) Regime of subterranean water flows in karst regions. In: Burger A, Dubertret L (eds) Hydrogeology of karstic terrains, Int Union Geol Sci Ser B 3. IAH, Paris, pp 68–78

Cai QW, Huang BX, Zhao XL, Xing YK, Liu SL (2023) Experimental investigation on the morphology of fracture networks in hydraulic fracturing for coal mass characterized by X-ray micro-computed tomography. Rock Mech Rock Eng. https://doi.org/10.1007/s00603-022-03210-1

Cao JR, Li QH, Cheng XS, Zheng G, Ha D, Zeng CF (2022) Study on artificial recharge and well loss in confined aquifers using theoretical and back-analysis calculations of hydrogeological parameters from recharge and pumping tests. Bull Eng Geol Environ. https://doi.org/10.1007/s10064-022-02988-2

Chandra S, Medha I, Tiwari AK (2023) The role of modified biochar for the remediation of coal mining-impacted contaminated soil: a review. Sustainability. https://doi.org/10.3390/su15053973

Chen X, He SM, Falinski MM, Wang YX, Li T, Zheng SX, Sun DY, Dai JQ, Bian YH, Zhu XB, Jiang JY, Hu LB, Ren ZJ (2021) Sustainable off-grid desalination of hypersaline waters using Janus wood evaporators. Energy Environ Sci 14(10):5347–5357. https://doi.org/10.1039/d1ee01505b

Chen G, Xu Z, Sun Y, Sui W, Li X, Zhao X, Liu Q (2022) Minewater deep transfer and storage. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.129848

Cognac KE, Ronayne MJ (2020) Changes to inter-aquifer exchange resulting from long-term pumping: implications for bedrock groundwater recharge. Hydrogeol J 28(4):1359–1370. https://doi.org/10.1007/s10040-020-02141-x

Fallatah OA, Ahmed M, Cardace D, Boving T, Akanda AS (2019) Assessment of modern recharge to arid region aquifers using an integrated geophysical, geochemical, and remote sensing approach. J Hydrol 569:600–611. https://doi.org/10.1016/j.jhydrol.2018.09.061

Gong DA, Yin YC, Chen HL, Guo B, Wu P, Wang Y, Yang Y, Li ZK, He Y, Zeng GF (2021) Interfacial ions sieving for ultrafast and complete desalination through 2D nanochannel defined graphene composite membranes. ACS Nano 15(6):9871–9881. https://doi.org/10.1021/acsnano.1c00987

He M, Li Q, Li XY (2022) A new simulator for hydromechanical coupling analysis of injection-induced fault activation. Geomech Geophys Geo-Energy Geo-Resour. https://doi.org/10.1007/s40948-022-00353-x

Kang G-d, Cao Y-m (2014) Application and modification of poly(vinylidene fluoride) (PVDF) membranes - a review. J Membr Sci 463:145–165. https://doi.org/10.1016/j.memsci.2014.03.055

Kang F, Shi Q, Ma Z, Sui H (2023) Genetic mechanism of the karst geothermal reservoir in buried uplifts of basins: a case study of Heze. Acta Geol Sin 97(1):221–237. https://doi.org/10.19762/j.cnki.dizhixuebao.2022017

Khadra WM, Stuyfzand PJ (2020) Problems and promise of managed recharge in karstified aquifers: the example of Lebanon. Water Int 45(1):23–38. https://doi.org/10.1080/02508060.2019.1682910

Li J, Chen JJ, Zhan HB, Li MG, Xia XH (2020a) Aquifer recharge using a partially penetrating well with clogging-induced permeability reduction. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.125391

Li LN, Xie DL, Wei JC, Yin HY, Li GH, Man XQ, Zhang WJ (2020b) Analysis and control of water inrush under high-pressure and complex karstic water-filling conditions. Environ Earth Sci. https://doi.org/10.1007/s12665-020-09242-6

Li XF, Peng B, Liu Q, Liu JW, Shang LW (2023) Micro and nanobubbles technologies as a new horizon for CO_2-EOR and CO_2 geological storage techniques: a review. Fuel. https://doi.org/10.1016/j.fuel.2023.127661

Liu QQ, Hanati G, Danierhan S, Zhang Y, Zhang ZP (2021a) Modeling of multiyear water-table fluctuations in response to intermittent artificial recharge. Hydrogeol J 29(7):2397–2410. https://doi.org/10.1007/s10040-021-02388-y

Liu Y, Gao X, Wang ZP, Wang K, Dou XY, Zhu HG, Yuan X, Pan LK (2021b) Controlled synthesis of bismuth oxychloride-carbon nanofiber hybrid materials as highly efficient electrodes for rocking-chair capacitive deionization. Chem Eng J. https://doi.org/10.1016/j.cej.2020.126326

Lu CH, Shi WL, Xin P, Wu JC, Werner AD (2017) Replenishing an unconfined coastal aquifer to control seawater intrusion: Injection or infiltration? Water Resour Res 53(6):4775–4786. https://doi.org/10.1002/2016WR019625

Manglik A, Rai SN (2015) Modeling water table fluctuations in anisotropic unconfined aquifer due to time varying recharge from multiple heterogeneous basins and pumping from multiple wells. Water Resour Manag 29(4):1019–1030. https://doi.org/10.1007/s11269-014-0857-y

Mitko K, Turek M (2021) Membrane-based solutions for the Polish coal mining industry. Membranes 11(8):638. https://doi.org/10.3390/membranes11080638

Mugova E, Wolkersdorfer C (2022) Density stratification and double-diffusive convection in mine pools of flooded underground mines—a review. Water Res. https://doi.org/10.1016/j.watres.2021.118033

Nguyen TS, Guglielmi Y, Graupner B, Rutqvist J (2019) Mathematical modelling of fault reactivation induced by water injection. Minerals 9(5):282. https://doi.org/10.3390/min9050282

Pinto PX, Al-Abed SR, Balz DA, Butler BA, Landy RB, Smith SJ (2016) Bench-scale and pilot-scale treatment technologies for the removal of total dissolved solids from coal mine water: a review. Mine Water Environ 35(1):94–112. https://doi.org/10.1007/s10230-015-0351-7

Pu L, Xin P, Yu XY, Li L, Barry DA (2021) Temperature of artificial freshwater recharge significantly affects salinity distributions in coastal confined aquifers. Adv Water Resour. https://doi.org/10.1016/j.advwatres.2021.104020

Sanayei HRZ, Javdanian H, Rakhshandehroo GR (2021) Assessment of confined aquifer response to recharge variations and water inflow distributions using analytical approach. Environ Sci Pollut Res 28(36):50878–50889. https://doi.org/10.1007/s11356-021-14314-6

Sendros A, Himi M, Lovera R, Rivero L, Garcia-Artigas R, Urruela A, Casas A (2020) Geophysical characterization of hydraulic properties around a managed aquifer recharge system over the Llobregat River alluvial aquifer (Barcelona metropolitan area). Water. https://doi.org/10.3390/w12123455

Shi TW, Pan YS, Zheng WH, Wang AW (2022) Influence of water injection pressure on methane gas displacement by coal seam water injection. Geofluids. https://doi.org/10.1155/2022/6208933

Spellman P, Breithaupt C, Bremner P, Gulley J, Jenson J, Lander M (2022) Analyzing recharge dynamics and storage in a thick, karstic vadose zone. Water Resour Res. https://doi.org/10.1029/2021WR031704

Sun XL, Yang PT, Zhang ZW (2017) A study of earthquakes induced by water injection in the Changning salt mine area, SW China. J Asian Earth Sci 136:102–109. https://doi.org/10.1016/j.jseaes.2017.01.030

Sun Y, Chen G, Xu Z, Yuan H, Zhang Y, Zhou L, Wang X, Zhang C, Zheng J (2020) Research progress of water environment, treatment and utilization in coal mining areas of China. Meitan Xuebao/ J China Coal Soc 45(1):304–316. https://doi.org/10.13225/j.cnki.jccs.YG19.1654

Sun Y, Zhang L, Xu Z, Chen G, Zhao X, Li X, Gao Y, Zhang S, Zhu L (2022) Multi-field action mechanism and research progress of coal mine water quality formation and evolution. Meitan Xuebao/ J China Coal Soc 47(1):423–437. https://doi.org/10.13225/j.cnki.jccs.YG21.1937

Thiruvenkatachari R, Francis M, Cunnington M, Su S (2016) Application of integrated forward and reverse osmosis for coal mine wastewater desalination. Sep Purif Technol 163:181–188. https://doi.org/10.1016/j.seppur.2016.02.034

van Lopik JH, Hartog N, Schotting RJ (2020) Taking advantage of aquifer heterogeneity in designing construction dewatering systems with partially penetrating recharge wells. Hydrogeol J 28(8):2833–2851. https://doi.org/10.1007/s10040-020-02226-7

Wang JX, Wu YB, Zhang XS, Liu Y, Yang TL, Feng B (2012) Field experiments and numerical simulations of confined aquifer response to multi-cycle recharge-recovery process through a well. J Hydrol 464:328–343. https://doi.org/10.1016/j.jhydrol.2012.07.018

Wang JL, Jin MG, Jia BJ, Kang FX (2015) Hydrochemical characteristics and geothermometry applications of thermal groundwater in northern Jinan, Shandong, China. Geothermics 57:185–195. https://doi.org/10.1016/j.geothermics.2015.07.002

Wang ZW, Chen HW, Li FL, Wang GX (2022) Experimental and simulation study on the impact of storage and recovery of coastal aquifer to seawater intrusion. Nat Hazards 114(1):237–259. https://doi.org/10.1007/s11069-022-05388-7

Xiong RH, Chen Q, Liu J, Wei C (2017) Experimental study on seeded precipitation assisted reverse osmosis for industrial wastewater reuse. J Water Process Eng 20:78–83. https://doi.org/10.1016/j.jwpe.2017.10.002

Yajun S, Zhimin X, Xin L, Li Z, Ge C, Xianming Z, Yating G, Qi L, Shangguo Z, Weijun W, Lulu Z, Sheng W (2021) Mine water drainage pollution in China's coal mining areas and the construction of prevention and control technical system. Coal Geol Explor 49(5):1–16. https://doi.org/10.3969/j.issn.1001-1986.2021.05.001

Zeng YF, Meng SH, Wu Q, Mei AS, Bu WY (2023) Ecological water security impact of large coal base development and its protection. J Hydrol. https://doi.org/10.1016/j.jhydrol.2023.129319

Zhang ZX, Wang WP (2021) Managing aquifer recharge with multi-source water to realize sustainable management of groundwater resources in Jinan. China Environ Sci Pollut Res 28(9):10872–10888. https://doi.org/10.1007/s11356-020-11353-3

Zhang YQ, Li MG, Wang JH, Chen JJ, Zhu YF (2017a) Field tests of pumping-recharge technology for deep confined aquifers and its application to a deep excavation. Eng Geol 228:249–259. https://doi.org/10.1016/j.enggeo.2017.08.019

Zhang YQ, Wang JH, Chen JJ, Li MG (2017b) Numerical study on the responses of groundwater and strata to pumping and recharge in a deep confined aquifer. J Hydrol 548:342–352. https://doi.org/10.1016/j.jhydrol.2017.03.018

Zhao HJ, Ma FS, Liu G, Feng XL, Guo J (2018) Analytical investigation of hydraulic fracture-induced seismicity and fault activation. Environ Earth Sci. https://doi.org/10.1007/s12665-018-7708-8