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TECHNICAL COMMUNICATION

An Optimized Combination of Mine Water Control, Treatment, Utilization, and Reinjection for Environmentally Sustainable Mining: A Case Study

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Abstract
This paper presents a case study of an optimized combination of mine water control, treatment, utilization and reinjection to achieve the zero discharge of mine water. Mine water has been considered a hazard and pollution source during underground mining, so most mining enterprises directly discharge mine water to the surface after simple treatment, resulting in a serious waste of water. Moreover, discharging a large amount of mine water can destroy the original groundwater balance and cause serious environmental problems, such as surface subsidence, water resource reduction and contamination, and adverse impacts on biodiversity. The Zhongguan iron mine is in the major groundwater source area of the Hundred Springs of Xingtai, which is an area with a high risk of potential subsidence. To optimize the balance between mining and groundwater resources, a series of engineering measures was adopted by the Zhongguan iron mine to realize mine water control, treatment, utilization, and reinjection. The installation of a closed grout curtain has greatly reduced the water yield of deep stopes in the mine; the effective sealing efficiency reaches 80%. Nanofiltration membrane separation was adopted to treat the highly mineralized mine water; the quality of the produced water meets China's recommended class II groundwater standard. Low-grade heat energy from the mine water is collected and utilized through a water-source heat pump system. Finally, zero mine water discharge is realized through mine water reinjection. This research provides a beneficial reference for mines with similar geological and hydrogeological conditions to achieve environmentally sustainable mining.

Keywords Subsidence · Mine curtain grouting · Nanofiltration · Ground source heat pump · Mine water reinjection

Introduction

Groundwater plays a crucial role in functioning and sustaining ecosystem balance, especially in arid and semiarid areas (Mishra and Singh 2010). Present-day groundwater development and utilization in many regions and industries are not sustainable, such as in the mining and metallurgy industry, which hints at options for restoring sustainability under favorable groundwater governance (Mays 2013). The exploitation of underground mineral resources must be accompanied by a large amount of water being drained away, which inevitably leads to eco-geo-environmental degradation and geological disasters, such as the massive deaths of low water-loving herbaceous vegetation, land subsidence, negative impacts on the water supply, reduction in surface water flows and spring discharges, and loss of wetlands (Herrera-García et al. 2021; Mays 2013; Yang et al. 2019).

In recent years, the geological and hydrogeological conditions of deep underground mines have become increasingly

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complex with the continuous increase in the depths of mines and mining intensity worldwide (Chen et al. 2021; Guo et al. 2019). Mine water is a direct hazard that threatens the safety of deep mining and has led to catastrophic water inrush accidents; the number of casualties and economic losses ranks first among all kinds of mine disasters in China. To reduce the risk of water inrush in underground stopes, grouting curtains are used to cut off the flow of groundwater on a regional scale. To date, nearly 100 mine grouting curtains have been installed in China, which can effectively control and reduce the risk of mine water inrush while also protecting the ecological environment of the mining area (Yuan and Han 2020; Yuan et al. 2021).

To reduce groundwater inflow, the Zhangmatun iron mine installed a grout curtain with a total length of 1410 m, thicknesses of 20–30 m, and depths of 330–560 m in 1996. The hydraulic head difference was maintained at 170–380 m between the inside and the outside of the curtain to ensure safe mine production (Zhou et al. 2017). Worldwide, many large-scale mining districts are in arid and rainless areas, such as the Yushenfu coalfield in northwest China. A large amount of mine water drainage aggravates the destruction of the ecological environment and land desertification (Liu et al. 2019; Wang et al. 2021a, b; Wu et al. 2017). Traditionally, the reuse of mine water can be divided into four types: industrial production (fire extinguishment, dust proofing, explosion protection, etc., with low-quality water), environmental purification (garden forestation, springs, and road dust suppression water), life activities (deeply treated water for drinking and bathing), and agricultural water for irrigation (Dharmappa et al. 2000; Kurbiel et al. 1996; Lambert et al. 2004; Liu and Liu 2010; Viadero and Tierney 2003).

Studies have shown that mine water can be used as a precious resource after treatment (Johnson and Hallberg 2005). Wu et al. (2017) proposed the concept of coal-water dual-resource mines based on the optimization of the mining method, separate underground discharge of clean water and sewage, intervention of hydrogeological conditions, and mining backfill, which realized targets for the control of water inrush risk, protection, and utilization of mine water, and improvement of the ecological environment. Qiao et al. (2020) presented a scientific approach for the coordinated exploitation of both coal and deep groundwater resources and explored the feasibility of using water pumped from dewatering wells to meet the water supply needs of local industry in the Xinglongzhuang coal mine, Shandong Province, eastern China.

Groundwater reinjection is a mature technology that has been widely used in groundwater funnel recharge, hydraulic fracturing, geothermal energy development, underground reservoirs, etc. The Cobre Las Cruces copper mine set up a complex drainage and reinjection system to store mine wastewater and preserve groundwater resources. Prior to injection, the drained water must be treated by reverse osmosis to remove metals and undesirable dissolved substances, with 91% water recovery (Baquero et al. 2016). Chen (2020) and Chen et al. (2022) carried out a series of field and laboratory tests to qualitatively and quantitatively evaluate the potential of the Liujiagou Formation as a mine water transfer and storage aquifer in the deep Ordos Basin. At present, there are few successful cases of mine water reinjection in China, namely, the Wutongzhuang coal mine, Zhongguan iron mine, and a few coal mines in the Mu Us Desert hinterland and Ordos basin, in northwest China (Zhao et al. 2021). Various methods of mine water control, treatment, utilization, and reinjection have been widely used in specific mines. However, these combined methods for the effective management of mine water have not achieved a successful case on a worldwide scale. Therefore, we tried to develop a more comprehensive approach to effectively manage mine water.

In 2011, the Zhongguan iron mine on the North China Plain (NCP) was selected as a test mine. The NCP region has suffered a serious shortage of water resources during China's economic boom. Groundwater piezometric levels in the NCP have cumulatively decreased by more than 70 m from 2006 to 2011 in many areas and locally exceed 100 m (Yin et al. 2016). The NCP is one of the most serious potential subsidence areas in the world, as shown in Fig. 1a (Herrera-García et al. 2021). The south-to-north water transfer project will enable 40 ~ 50 billion m^3 of water to be transferred annually from the Yangtze River to northern China, thus solving water shortage problems for 300 ~ 325 million people (Zhang 2009). Therefore, it is urgent to protect the NCP's groundwater resources. In 2017, Hebei Province designated a total groundwater mining prohibition area of 2,495.8 km^2 and a groundwater mining restricted area of 40,329.3 km^2.

Mine drainage from iron mines and coal mines contributed 42% of the observed groundwater depletion in Xingtai city, NCP (Yin et al. 2016). The Zhongguan iron mine has much high-quality ore and is in the groundwater mining-restricted area of Hebei Province. Therefore, the Zhongguan iron mine was not mined until 34 years after geological exploration was completed due to the extremely rich groundwater supply of the ≈ 200 m thick Ordovician limestone aquifer (Han et al. 2009). This paper introduces a series of engineering measures that have been adopted by the Zhongguan iron mine to realize mine water control, treatment, utilization, and reinjection. We hope this example of combined mine water methods can serve as a beneficial reference for mines with similar geological and hydrogeological conditions to achieve environmentally sustainable mining.

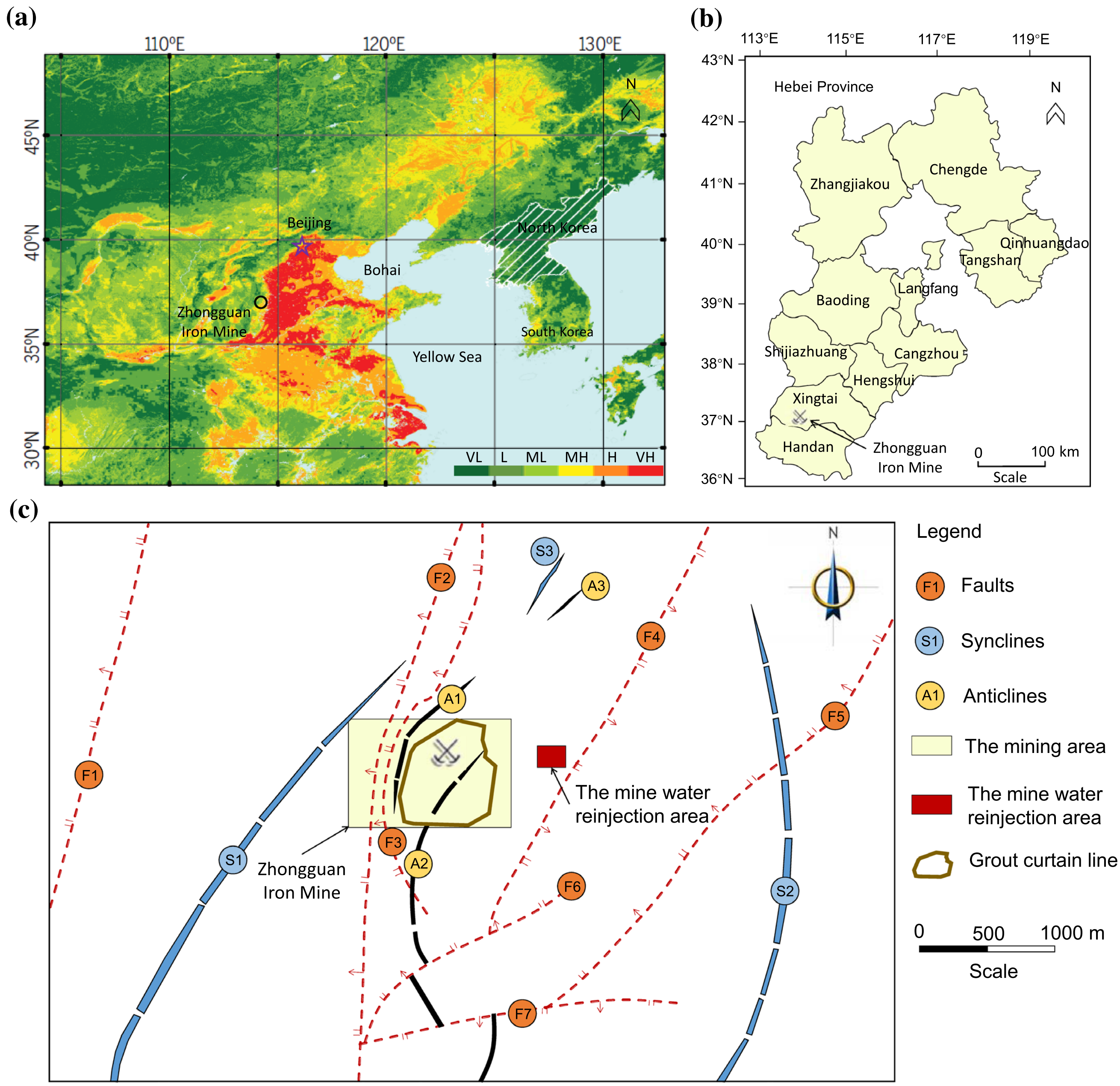

Fig. 1 Map showing the study area. **a** Potential subsidence of the east Asian area (modified from Herrera-García et al. 2021). The color scale indicates the probability intervals classified from very low (VL) to very high (VH) for every 30 arc sec resolution pixel (1 km by 1 km at the equator). The white hatched polygons indicate countries where groundwater data are unavailable, and the potential subsidence includes information on only the susceptibility. **b** Location of the Zhongguan iron mine, Xingtai city, Hebei, China. **c** Regional tectonic outline map

Geological Setting and Hydrogeological Engineering Conditions

Zhongguan Iron Mine

The Zhongguan iron mine is in Xingtai city, north China, at 36°55′N longitude and 114°01′E latitude (Fig. 1). The mine encompasses an area of ≈ 5.0 km^2, with a length of 2500 m in the north-to-south direction and a width of 2000 m in the east-to-west direction. The elevation of the mining area ranges from 200 to 280 m above sea level (asl). The study area has a warm temperate continental monsoon climate with an annual rainfall of 540 mm and defined seasons; more than 80% of the rainfall occurs from July to September. The annual average maximum evaporation occurs in July and reaches 1090 mm. The geometrical shape of the ore body is very irregular, with an average thickness of 38 m, a maximum burial depth of 850 m and a total resource reserve of 93.45 million tons. By 2008, the regional groundwater table had been lowered by 156 m by the completion of a closed grouting curtain, greatly improving mining conditions.

Geological Conditions

Geologically, the Zhongguan iron mine is in the eastern foot of the middle part of the Taihang Mountains, with a mountainous area in the west and a plains area in the east. The Taihang Mountains are located at the boundary between Hebei province and Shanxi province; the mountains extend to the boundary between Henan and Shanxi toward the south, have a northeast-southwest alignment, and continue for several hundred kilometers, making them an important geographical boundary in eastern China and a natural boundary between the Loess Plateau and the NCP. The stratigraphy of the study area consists of Holocene strata, a Permian formation of interbedded sandstone and shale, an upper Paleozoic Carboniferous formation, lower Paleozoic Ordovician limestone, and Yanshanian Formation altered diorite. The mineral deposit is a magnetite ore body containing contact metasomatic skarn and is mainly distributed in the contact zone of the Yanshanian diorite and Ordovician limestone. The detailed stratigraphic structure of the mining area is shown in Table 1. The mineral deposit has a length of 2000 m, width of 800 m, average thickness of 38 m, maximum thickness of 193.06 m, burial depths of 730–850 m, and total reserves of 93.45 million t. Regionally, NNE- and NE-trending faults are mainly present, and there are two secondary faults, F2 and F3, in the mining area.

Hydrogeological Conditions

Regionally, the Zhongguan iron mine is in the major groundwater source area of Hundred Springs (3843 km^2) in Xingtai, which is one of the major water supply sources for Xingtai city. Three aquifers in the study area affect the safety of deep underground mining. From top to bottom, these are a sand and gravel aquifer in the lower Quaternary strata, a thin limestone interbedded sandstone and shale fractured aquifer in the Permian strata and a limestone karst aquifer in the Middle Ordovician with an average thickness of ≈ 200 m, which is the water-filling source associated with the roof water inrush and which directly threatens the deep mining safety. The Ordovician limestone karst aquifer is the main water-filling aquifer in the mining area and is characterized by high permeability and water abundance, with an average unit water inflow of 3.68 L/(s·m). According to the local hydrometeorological data, the rainfall amounts in the mining areas in wet years, normal years, and dry years are 800 mm, 450 mm, and 300 mm, respectively. The Sha River is in the northwestern part of the mining area and is a seasonal river with a maximum flow of 125 m^3/s from July to September every year. The surface water of the Sha River is closely connected with the groundwater in the mining area. Therefore, the hydrogeological conditions of the mining area are extremely complicated and have massive dynamic and static water reserves.

Methodology

Mine Water Control—Grout Curtain

In China, mine curtain grouting has been widely used in metal and nonmetal mines to control mine water (Yuan and

Table 1 Detailed stratigraphic structure of the Zhongguan iron mine

Stratigraphic unit			Thickness (m)	Lithology	Remarks
System	Formation	Symbol			
Quaternary	–	Q	30–100	Loess, gravelly clay, silt, silty sand, and silty fine sand	Yellowish brown, mainly distributed in low-lying areas and the edges of rivers and lakes
Permian	–	P	580–1036	Interbedded sandstone and shale	Grayish white, dark gray, large thick layer
Carboniferous	Taiyuan	C_3t	115–145	Sandy shale intercalated with several layers of thin limestone and a minable coal seam	Dark gray, blocky, medium thick to thick layer
	Benxi	C_2b	11–55	Bauxite shale, sandstone and mudstone	Dark gray, thick layer, unconformable contact relationship with underlying strata
Ordovician	Majiagou	O_2m	448–639	Limestone and dolomitic limestone, altered diorite, and a major iron ore deposit hosted in the strata	Grayish white, thick to large thick layer, Yanshanian magmatic intrusion
	Liangjiashan	O_1l	65–268	Dolomitic limestone and dolomite	Grayish white, medium thick to thick layer
Cambrian	–	∈	283–627	Interbedded shale and sandstone and limestone	Purple, oolitic, bamboo leaf-shaped and banded limestone

Han 2020). Mine curtain grouting refers to using drillings and grouting equipment on the surface or underground to inject a coagulable slurry into the cracks or pores of the rock mass to cut off groundwater flow, thereby forming a curtain-shaped artificial water barrier with a certain thickness around the ore body to reduce the water yield inside the grout curtain. To reduce the water yield of deep mining and protect the regional groundwater resources, a 3393 m long, 10 m wide grout curtain was installed in the Zhongguan iron mine from January 2011 to October 2015. Approximately 89% of the ore reserves in the mine are now enclosed by the grout curtain. Curtain grouting reduced water inflow into the mine by 80% and recharged the Hundred Springs area of Xingtai (Li et al. 2011; Song and Liu 2012; Yuan and Han 2020). The schematic relationship of the grout curtain with the ore body, as well as the groundwater and formation interaction in the Zhongguan iron mine is shown in Fig. 2. Long-term monitoring of the water level inside and outside the curtain indicated that the maximum water level difference was 27 m. More detailed water level monitoring data can be obtained from the articles of Shi et al. (2017) and Shi et al. (2018).

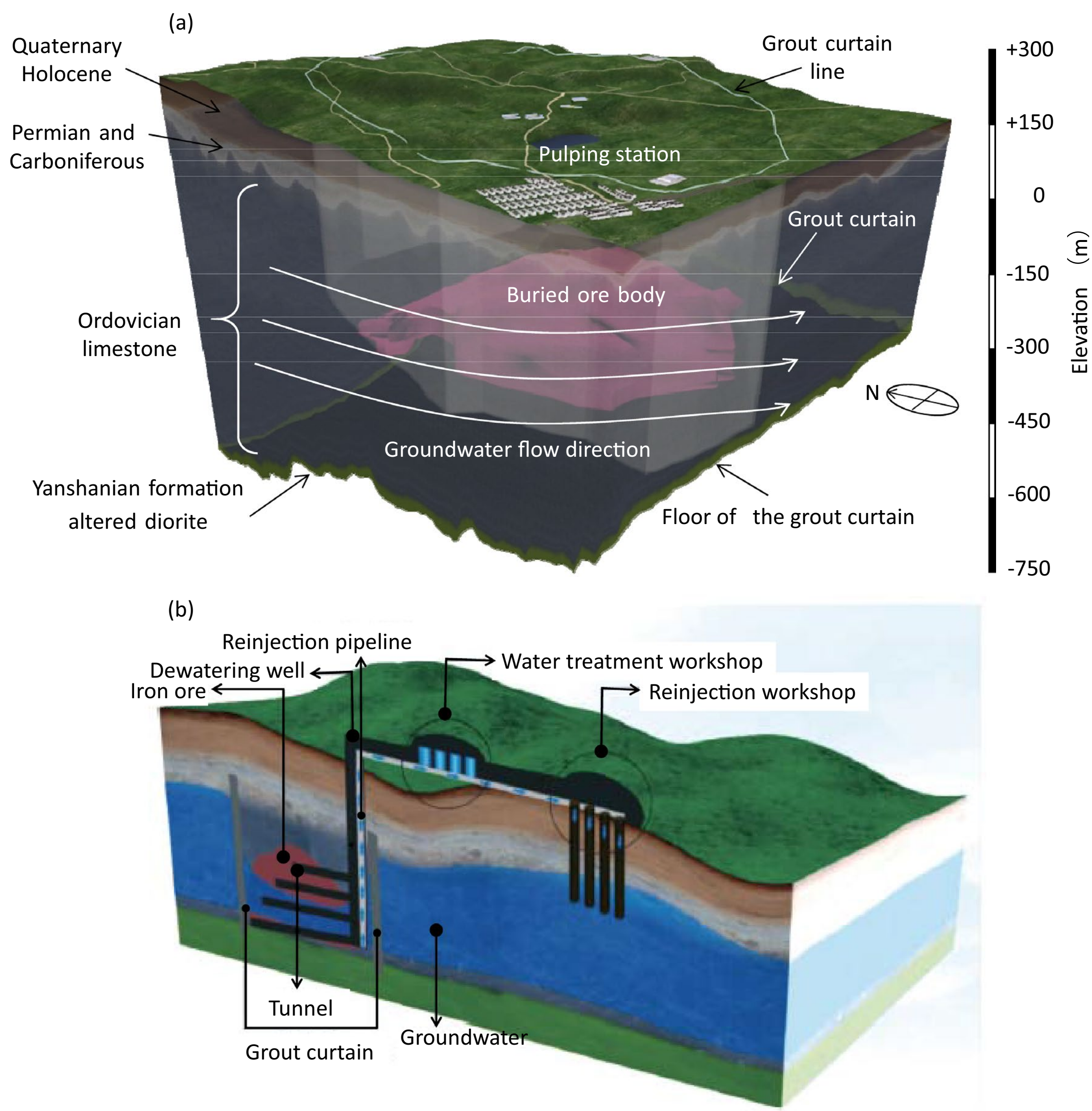

Fig. 2 **a** Schematic relationship of the grouting curtain with the ore body, groundwater and formation in the Zhongguan iron mine. **b** Schematic diagram of the overall mine water management system

Mine Water Treatment—Membrane Separation

Membrane separation can be used to separate, purify and concentrate mine water with natural or synthetic polymer membranes as the medium and external energy or chemical potential differences as the driving force (supplemental Fig. S-1); this technique has the advantages of high efficiency, low energy consumption, easy operation, and environmental friendliness (Loganathan et al. 2015; Mullett et al. 2014). Nanofiltration (NF) was adopted by the Zhongguan iron mine to treat the highly mineralized mine water. The main component of a NF membrane is polyamide. The pore size of the NF membrane is approximately 1 nm, between the 0.1 nm reverse osmosis membrane and the 10 nm ultrafiltration membrane. Compared with reverse osmosis, the NF process has a lower operating pressure and ≈ 30% lower initial investment and operating cost. The NF membrane rejects ≈ 50% of the dissolved monovalent ions and more than 90% of the dissolved divalent ions in the mine water. Basically, it can remove harmful substances from mine water and has the dual functions of purifying and softening water.

Mine Water Utilization—Heat Pump System

Heat pump (HP) technology has been widely used for upgrading ambient heat from sustainable sources, such as air, water, ground, and waste heat, to heating temperatures (Watzlaf and Ackkman 2006). The technology can be used for residential and commercial space heating, cooling, water heating, refrigeration, and many industrial processes (supplemental Fig. S-2). An HP system does not create heat by burning fuel, like a furnace. As a result, it is one of the cleanest technologies available for transferring heat to and from a natural heat source or sink. Therefore, the use of HP technology is beneficial to energy conservation and environmental protection, though traditional working fluids can damage the ozone layer and cause greenhouse effects (Chua et al. 2010). Employing HPs for residential heating and cooling can markedly reduce carbon emissions. According to a CO_2 emission study conducted in Japan, a typical residential ground source heat pump (GSHP) produces only ≈ 2038 kg CO_2/year, which is less than half that of conventional boiler systems (Nagano et al. 2006).

Mine Water Reinjection

Groundwater reinjection has been widely applied in many fields, such as the exploitation and utilization of geothermal resources, control and treatment of surface subsidence caused by groundwater overdraft, construction of groundwater reservoirs, and control of seawater intrusion (Chen 2020; Gu 2015; Kaya et al. 2011; Rivera et al. 2016; Saripalli et al. 2020). Groundwater reinjection into aquifers can be used to reconstruct the regional hydrogeological system. Seven hydrogeological factors, viz., hydraulic gradient, water table buried depth, soil or rock mass properties, drainage, infiltration, lithology and land use, generally define the most suitable locations for artificial groundwater reinjection in mining areas (Tiwari et al. 2017). Mine water reinjection can be used to reduce the impact of mining activities on groundwater resources, balance the regional ecological environment, and reduce surface subsidence, ground collapse, and other geological disasters. However, it is necessary to consider and evaluate the relative bearing capacity of the target reinjection aquifer, the sealing and capacity of the regional hydrogeological unit, and the risk of mine water inrush caused by the increase in the aquifer's water pressure (Sun et al. 2020).

Results and Discussion

Grout Curtain Effectiveness

Crosshole resistivity tomography was used to detect the grouting effectiveness in the Zhongguan iron mine; this method is a highly accurate electrical prospecting technique. The geophysical instrument used in this study was the FlashRES64-61 channel system, which was developed by ZZ Resistivity Imaging Pty. Ltd., Australia, as shown in Fig. 3a–c. The technical specifications of the FlashRES64-61 channel system are listed in Table 2. The distance between boreholes W2 and W3 was 60 m, and there were four grouting boreholes, namely, W201, W202, W203 and W204, between them. Clay-cement grout was used in this mine curtain grouting and water plugging project. The detection results before and after the grouting of boreholes W2 and W3 at depths of 150–350 m are shown in Fig. 3d, e, which show that the high resistivity area was obviously enlarged and the low resistivity area obviously lessened after grouting, which indicates that the grouting obviously improved the continuity and strength of the surrounding rocks.

Water Treatment

The installation of the grout curtain greatly reduced the water yield of deep stopes in the Zhongguan iron mine; the effective sealing efficiency reached 80%. However, the residual water yield is still ≈ 24,800 m^3/day. So, a NF membrane separation system with a treatment capacity of 1000 m^3/h was installed in the Zhongguan iron mine. The mine water flowing through the NF membrane separation system needs to be mechanically filtered to remove sediment and suspended matter. The quality of the produced water meets the class II groundwater standard recommended in China's "Standard for Groundwater Quality" (GB/T14848-2017;

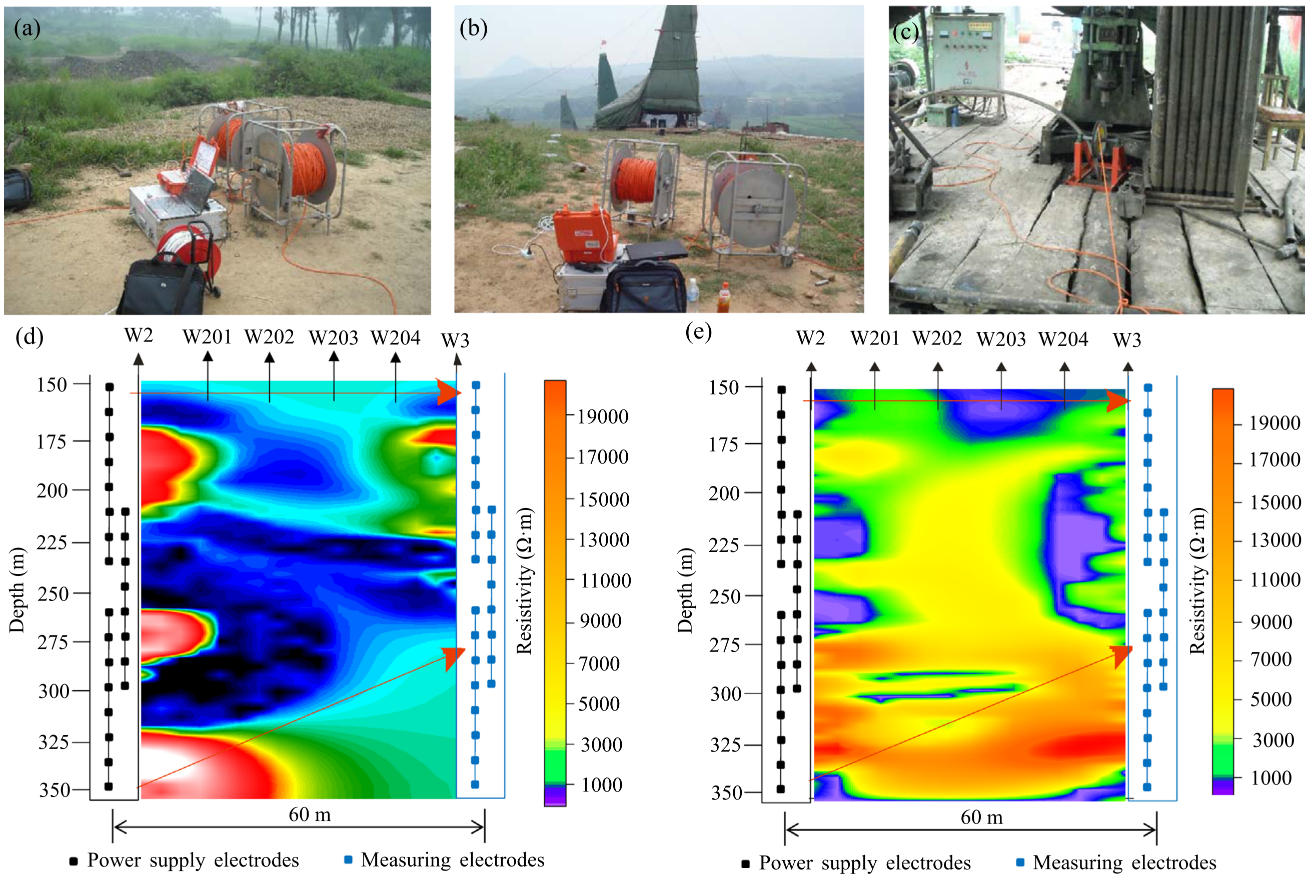

Fig. 3 Field test instruments and results of the grouting effect. **a, b** Photographs of the FlashRES64-61 channel system. **c** Photograph of the W2 test borehole. **d, e** The test results of crosshole resistivity tomography between W2 and W3 before and after grouting

Table 2 Technical specifications of the FlashRES64-61 channel system used in this study

Technical specifications	Values
Electrodes	64
Channels	61
Accuracy	< 0.5%
Suppression of 50 Hz power frequency interference	> 80 dB
Output DC voltage	30 V, 90 V, 250 V
Input voltage	± 5 V
Input impedance	> 107 MΩ
Measuring current range	< 3 A
Operating temperature	−20 ℃ to + 50 ℃
Operating humidity	95% RH
Weight	4.5 kg
Dimensions (L × W × H)	350 mm × 300 mm × 150 mm

Standardization Administration of China 2017). The water recovery rate of the NF membrane separation system exceeds 90%, and the 10% concentrated water is used as part of the underground mine's production water in the Zhongguan iron mine. The treated mine water is mainly used in the following ways: mining area production, greening, dust-proofing water, industrial supplementary water for nearby enterprises, irrigation water, and living water for residents. The water quality values of the native groundwater, ultrafiltration-rejected water, and injection water are shown in Table 3.

Water-Source Heat Pump System

The mine water temperature of the Zhongguan iron mine remains at ≈ 18 ℃ throughout the year, with a large amount of low-grade heat energy. The low-grade heat energy of the mine water was collected and utilized through a water-source heat pump (WSHP) system. The average heat load of the total mining area is ≈ 11,755 kW, with 5% pipeline network loss. Considering the temperature of the mine water and the average heat load of the total mining area, the water demand of the WSHP system is ≈ 800 m^3/h. The use of WSHP technology in the Zhongguan iron mine addresses the practical problems of summer cooling and winter heating of residential areas, freeze protection for water pipes, miner bathing,

Table 3 Water quality of native groundwater, ultrafiltration-rejected water and injection water

Water quality	Total hardness	TDS	Fluoride	Fe	Mn
Native groundwater (mg/L)	537	1243	0.32	0.13	0.01
Ultrafiltration-rejected water (mg/L)	305	560	0.19	0.01	0.01
Injection water (mg/L)	415	709	0.22	0.01	0.01
Class II groundwater (GB/T14848-2017)	≤300	≤500	≤1.0	≤0.2	≤0.05

and mining production. In addition, the coal-fired boilers and central air conditioning are replaced by the WSHP system in the Zhongguan iron mine, which significantly reduces the carbon emissions and production costs.

Mine Water Reinjection

The Zhongguan iron mine is in the major groundwater source area of Xingtai's Hundred Springs (3843 km^2). The Ordovician limestone karst aquifer is the main water-filling aquifer and has an average unit water inflow of 3.68 L/(s·m). Influenced by the regional structure framework, the water abundance of the Ordovician limestone karst aquifer has been characterized as "strong in the east and weak in the west" in the mining area, which controls groundwater migration and accumulation. Based on three large-scale pumping tests conducted in the Zhongguan iron mine from 1960 to 1974, the Ordovician limestone karst aquifer in the east of the mining area has strong water permeability, and the groundwater runoff in the mining area is mainly affected by the regional structural framework. Therefore, the favorable area of mine water reinjection is in the Ordovician limestone karst aquifer to the east of the mining area. Comprehensive analysis of the regional structure framework, geological and hydrogeological conditions, geomorphologic characteristics of the favorable area, and two mine water reinjection well (G1 and G2) locations were identified ≈ 250 m and 300 m east of the mining area, respectively, with six observation wells (GS1, HG1, HG2, HG3, HG4, and HG5) distributed around G1 and G2, as shown in Fig. 4. The water absorption index (WAI) is used to evaluate the water absorption capacity of the mine water reinjection wells and can be calculated by Formula (1); the WAIs of G1 and G2 in different well sections are listed in Table 4.

$$WAI = \frac{Q}{P_2 - P_1} \tag{1}$$

where WAI is the water absorption index, in m^3/(h·MPa); Q is the water reinjection flow, in m^3/h; P_1 is the bottom well pressure before reinjection, in MPa; and P_2 is the bottom well pressure after reinjection, in MPa.

Table 4 shows that the WAIs of G1 and G2 reinjection wells vary greatly in different well sections. The −179 to −300 m well sections of the G1 and G2 reinjection wells have a relatively considerable and stable water absorption capacity. Moreover, when G1 and G2 are reinjected together at a water flow of 200 m^3/h, the WAI reaches 1052. The water level rise data in the GS1, HG1, HG2, HG3, HG4, and HG5 observation wells are recorded during water reinjection and the contour maps of the rising water level are shown in Fig. 4. Figure 4a shows the groundwater seepage responses of −179 to −300 m in G1, with a reinjection flow of 140.51 m^3/h. Figure 4b shows the groundwater seepage responses of G1 and G2 at −179 to −300 m, with a reinjection flow of 200 m^3/h. It can be concluded from Fig. 4 that the main diffusion direction of the reinjected water is to the northeast of the mining area.

Zero Discharge of Mine Water

The zero discharge of mine water is a mine water management strategy that eliminates mine wastewater and maximizes mine water usage efficiency, which has attracted renewed interest worldwide in recent years (Tong and Elimelech 2016). Mine water recovery and recycling minimizes the volume and potential environmental risk of discharged mine water and alleviates the pressure on ecosystems resulting from groundwater withdrawal. Mine water is no longer considered a "wastewater" that potentially harms the environment but rather an additional resource that can be harnessed to achieve environmentally sustainable mining (Grant et al. 2012; Tong and Elimelech 2016).

Figure 5 shows the concept mapping of mine water zero discharge through mine water control, treatment, utilization, and reinjection. In the Zhongguan iron mine, a series of engineering measures have been implemented, resulting in large ecological benefits. The regional groundwater level has risen by 30–50 m, and the springs have resumed flow. Moreover, it ensures the safety of Xingtai's water supply source. According to the average heat load of the Zhongguan iron mine, the annual total heat consumption is ≈ 11,755 kW. If the traditional boiler heating method was adopted, a large amount of standard coal would be consumed. These standard coals not only need to occupy a special place for storage, but also produce a large amount of dust and harmful gas in the combustion process. After the heating and cooling load of the Zhongguan iron mine is provided by the WSHP system, 7100 tons of standard

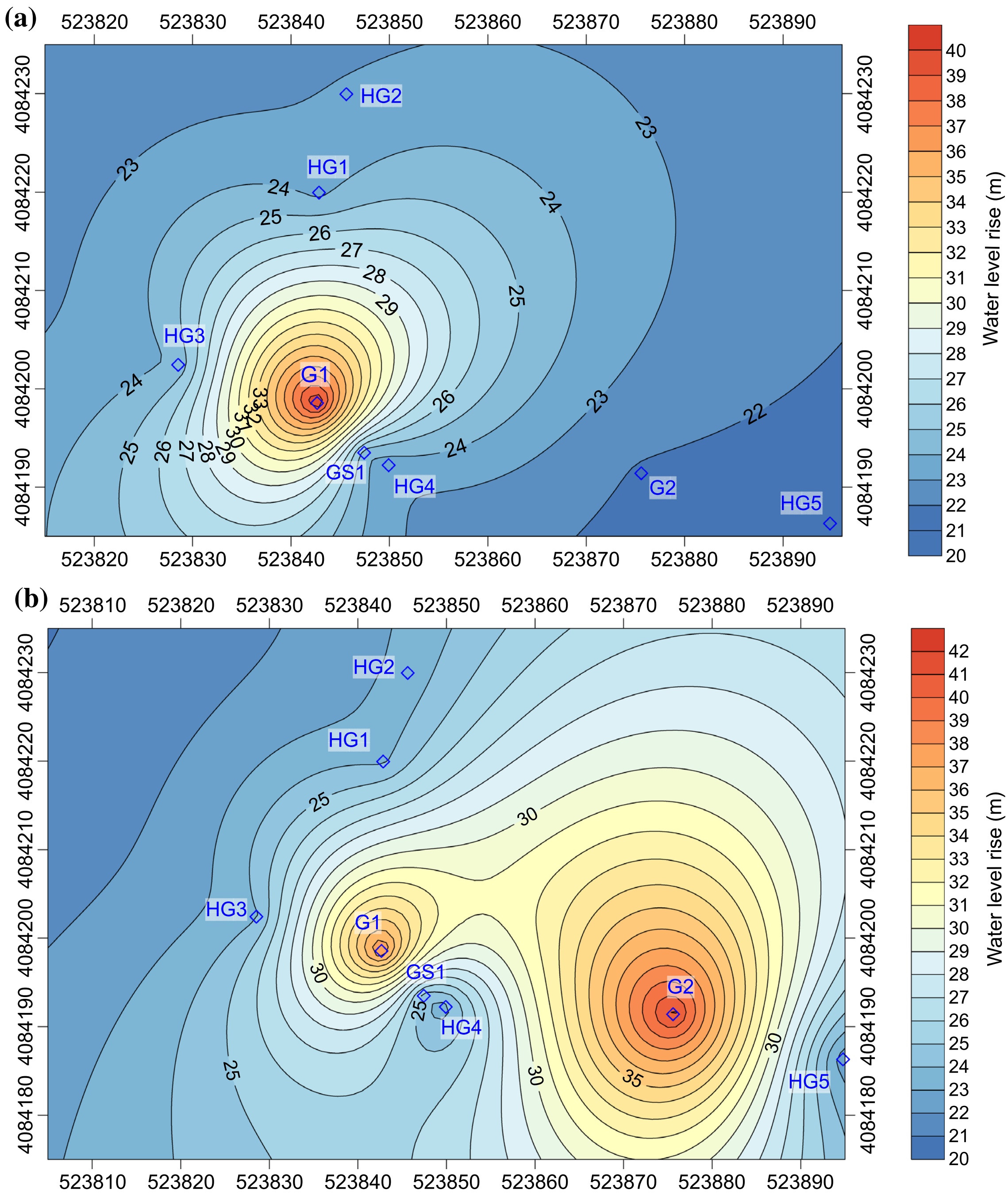

Fig. 4 Groundwater seepage responses: **a** −179 to − 300 m in G1, with a reinjection flow of 140.5 m³/h; **b** −179 to −300 m in G1 and G2, with a reinjection flow of 200 m³/h

coal, 16,000 tons of CO_2 emissions, and 86.4 tons of SO_2 emissions can be reduced every year (Han and Yuan 2019; Ren et al. 2019). The successful case of the Zhongguan iron mine provides a beneficial reference for mines with similar geological and hydrogeological conditions to achieve the zero discharge of mine water strategy.

Economics

Obviously, the early investment costs of such a set of mine water management systems are larger and consume a lot of time. Therefore, a full feasibility investigation and argument should be conducted before implementation. At the same time, the establishment of such a mine water

Table 4 WAIs of G1 and G2 in different well sections

Reinjection wells	Well section (m)	Lithology	Reinjection flow (m^3/h)	$\Delta P = P_2 - P_1$ (MPa)	WAI ($m^3/(h \cdot MPa)$)
G1	+96 to +1	Silty sand	62.81	0.83	75.67
			80.42	0.95	84.65
			101.87	1.05	97.02
	+1 to −79	Sandstone	61.11	0.05	1222.20
			87.75	0.25	351.00
	−179 to −300	Limestone	140.51	0.20	702.55
			170.58	0.25	682.32
G2	+83.4 to −79	Sandstone	10.21	0.62	16.13
			20.53	0.66	30.30
			40.65	0.69	57.97
			60.95	0.71	84.50
	−179 to −300	Limestone	100.05	0.20	500.00
G1 and G2	−179 to −300	Limestone	200.00	0.19	1052.00

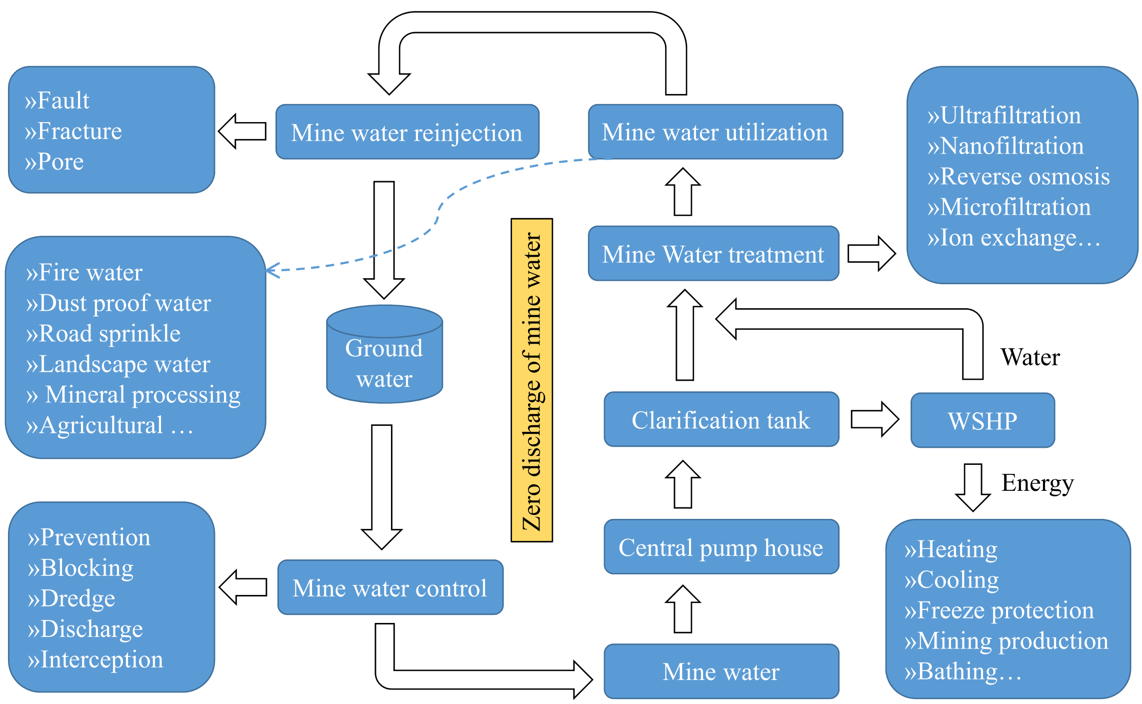

Fig. 5 Concept mapping of the zero discharge of mine water strategy

management system can result in significant savings in power and equipment costs, as well as in significant environmental and ecological benefits, all of which must be considered. The Zhongguan iron mine is saving 1.5 million RMB yuan (well over a quarter million U.S. dollars) per year just based on the cost of electricity for drainage. Moreover, the surface ecology and groundwater resources around the mining area are effectively protected.

Limitations and Further Study

The focus of this study was to introduce an optimized combined method to achieve the efficient management of mine water and environmentally sustainable mining, especially in areas where groundwater resources are extremely scarce, or the ecological environment is extremely fragile. Therefore, this article does not contain a great deal of site-specific technical details. The successful implementation of this series of engineering methods in the Zhongguan iron mine started at the beginning of the twenty-first century and has been operated for more than 10 years. A full assessment of the restoration degree of the surface ecological environment around the mining area will be completed in the future.

Summary and Conclusion

A combination of mine water control, treatment, utilization, and reinjection technologies has been used to achieve environmentally sustainable mining at the Zhongguan iron mine in Hebei Province, China, which is in the major groundwater source area of the Hundred Springs of Xingtai. To optimize the balance between mining and groundwater resources, a series of engineering measures were adopted. A closed grout curtain reduced the water yield of the mine's deep stopes by 80%. The residual water yield was treated by NF, and the quality of the produced water meets the recommended class II groundwater standard. The low-grade heat energy from the mine water was collected and utilized through a WSHP system. Finally, zero discharge of mine water was realized by mine water reinjection. The mine is saving 1.5 million yuan per year in electricity that would have been consumed by drainage. Moreover, the surface ecology and groundwater resources around the mining area have been effectively protected. The control, treatment, utilization, and reinjection of mine water resulted in large ecological benefits, such as regional groundwater level rise, spring reflow, and carbon emission reduction. This case study provides a reference for similar mines who seek to achieve environmentally sustainable mining. However, we must emphasize that the successful experience of the Zhongguan iron mine cannot be wholly copied by any mine. Each mine must explore its own sustainable development path.

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References

Baquero JC, Reyes MJ, Custodio E, Scheiber L, Vázquez-Suñé E (2016) Groundwater management in mining: the drainage and reinjection system in Cobre Las Cruces. Spain Mod Environ Sci Eng 2(10):631–646

Chen W, Li W, Wang Q, Qiao W (2021) Evaluation of groundwater inflow into an iron mine surrounded by an imperfect grout curtain. Mine Water Environ 40(2):520–538

Chen G, Xu ZM, Sun YJ, Sui WH, Li X, Zhao XM, Liu Q (2022) Mine water deep transfer and storage. J Clean Prod 332:129848

Chen G (2020) Study on the deep transfer and storage mechanism of mine water in the eastern margin of Ordos basin. China University of Mining and Technology, Xuzhou, pp 129–138 **(in Chinese, with abstract in English)**

Chua KJ, Chou SK, Yang WM (2010) Advances in heat pump systems: a review. Appl Energy 87(12):3611–3624

Dharmappa HB, Wingrove K, Sivakumar M, Singh R (2000) Wastewater and stormwater minimisation in a coal mine. J Clean Prod 8(1):23–34

Grant SB, Saphores JD, Feldman DL, Hamilton AJ, Fletcher TD, Cook PLM, Stewardson M, Sanders BF, Levin LA, Ambrose RF, Deletic A, Brown R, Jiang SC, Rosso D, Cooper WJ, Marusic I (2012) Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability. Science 337(6095):681–686

Gu D (2015) Theory framework and technological system of coal mine underground reservoir. J Chin Coal Soc 40(2):239–246 **(in Chinese with abstract in English)**

Guo J, Ma L, Zhang D (2019) Management and utilization of high-pressure floor-confined water in deep coal mines. Mine Water Environ 38:780–797

Han G, Yuan S (2019) Key technologies of comprehensive treatment of mine water in water-rich mines. China University of Geosciences Press, Wuhan **(in Chinese)**

Han G, Yu T, Liu D, Jiang P, Wang Q, Tang Y (2009) Effect evaluation and cross-well resistivity technology for the deep-hole curtain grouting in the Zhongguan iron mine. Geol Surv Res 32(1):69–74

Herrera-García G, Ezquerro P, Tomás R, Béjar-Pizarro M, López-Vinielles J, Rossi M, Mateos RM, Carreón-Freyre D, Lambert J, Teatini P, Cabral-Cano E, Erkens G, Galloway D, Hung WC, Kakar N, Sneed M, Tosi L, Wang H, Ye S (2021) Mapping the global threat of land subsidence. Science 371(6254):34–36

Johnson DB, Hallberg KB (2005) Acid mine drainage remediation options: a review. Sci Total Environ 338(1–2):3–14

Kaya E, Zarrouk SJ, O'Sullivan MJ (2011) Reinjection in geothermal fields: a review of worldwide experience. Renew Sust Energ Rev 15(1):47–68

Kurbiel J, Balcerzak W, Rybicki SM, Świst K (1996) Selection of the best desalination technology for highly saline drainage water from coal mines in southern Poland. Desalination 106(1–3):415–418

Lambert DC, McDonough KM, Dzombak DA (2004) Long-term changes in quality of discharge water from abandoned underground coal mines in Uniontown Syncline, Fayette County, PA, USA. Water Res 38(2):277–288

Li Z, Guo D, Wang Y, Zhen Z (2011) Technology research of large underwater ultra-deep curtain grouting in Zhong-Guan iron ore. Procedia Eng 26:731–737

Liu S, Li W (2019) Indicators sensitivity analysis for environmental engineering geological patterns caused by underground coal mining with integrating variable weight theory and improved matter-element extension model. Sci Total Environ 686:606–618

Liu H, Liu Z (2010) Recycling utilization patterns of coal mining waste in China. Resour Conserv Recy 54:1331–1340

Loganathan K, Chelme-Ayala P, El-Din MG (2015) Treatment of basal water using a hybrid electrodialysis reversal-reverse osmosis system combined with a low-temperature crystallizer for near-zero liquid discharge. Desalination 363(S1):92–98

Mays LW (2013) Groundwater resources sustainability: past, present, and future. Water Resour Manag 27(13):4409–4424

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391(1–2):204–216

Mullett M, Fornarelli R, Ralph D (2014) Nanofiltration of mine water: impact of feed pH and membrane charge on resource recovery and waste discharge. Membranes 4(2):163–180

Nagano K, Katsura T, Takeda S (2006) Development of a design and performance prediction tool for the ground source heat pump system. Appl Therm Eng 26(14–15):1578–1592

Qiao W, Howard KWF, Li W, Zhang S, Zhang X, Niu Y (2020) Coordinated exploitation of both coal and deep groundwater resources. Environ Earth Sci 79:120

Ren X, Cheng X, Wang W, Han H (2019) Comprehensive utilization technology of mine water based on "two cycle". Hebei Metall 285:79–82 **(in Chinese, with abstract in English)**

Rivera Diaz A, Kaya E, Zarouk SJ (2016) Reinjection in geothermal fields—a worldwide review update. Renew Sust Energ Rev 53:105–162

Saripalli KP, Sharma MM, Bryant SL (2020) Modeling injection well performance during deep-well injection of liquid wastes. J Hydrol 227(1):41–55

Shi W, Yang T, Yu Q, Li Y, Liu H, Zhao Y (2017) A study of water-inrush mechanisms based on geo-mechanical analysis and an in-situ groundwater investigation in the Zhongguan iron mine, China. Mine Water Environ 36(3):409–417

Shi W, Yang T, Liu H, Yang B (2018) Numerical modeling of non-Darcy flow behavior of groundwater outburst through fault using the Forchheimer equation. J Hydrol Eng 23(2):04017062

Song F, Liu XS (2012) Technical achievements of curtain grouting project in Zhongguan iron mine. China Univ of Geosciences Press, Wuhan **(in Chinese)**

Standardization Administration of China (2017) Standard for groundwater quality (GB/T14848-2017). Standards Press of China, Beijing, pp 2–5 **(in Chinese)**

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. J Chin Coal Soc 45(1):304–316 **(in Chinese with abstract in English)**

Tiwari AK, Lavy M, Amanzio G, Maio MD, Singh PK, Mahato MK (2017) Identification of artificial groundwater recharging zone using a GIS-based fuzzy logic approach: a case study in a coal mine area of the Damodar Valley, India. Appl Water Sci 7:4513–4524

Tong T, Elimelech M (2016) The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. Environ Sci Technol 50(13):6846–6855

Viadero RC, Tierney AE (2003) Use of treated mine water for rainbow trout (*Oncorhynchus mykiss*) culture—a preliminary assessment. Aquacult Eng 29(1–2):43–56

Wang W, Zhang Z, Yin L, Duan L, Huang J (2021a) Topical collection: groundwater recharge and discharge in arid and semi-arid areas of China. Hydrogeol J 29(2):521–524

Wang W, Zhao J, Duan L (2021b) Simulation of irrigation-induced groundwater recharge in an arid area of China. Hydrogeol J 29(2):525–540

Watzlaf GR, Ackkman TE (2006) Underground mine water for heating and cooling using geothermal heat pump systems. Mine Water Environ 25:1–14

Wu Q, Shen J, Wang Y (2017) Mining techniques and engineering application for "Coal-Water" dual-resources mine. J Chin Coal Soc 42(1):8–16 **(in Chinese with abstract in English)**

Yang Z, Li W, Li X, Wang Q, He J (2019) Assessment of eco-geo-environment quality using multivariate data: a case study in a coal mining area of western China. Ecol Indic 107:105651

Yin S, Han Y, Zhang Y, Zhang J (2016) Depletion control and analysis for groundwater protection and sustainability in the Xingtai region of China. Environ Earth Sci 75:1246

Yuan S, Han G (2020) Combined drilling methods to install grout curtains in a deep underground mine: a case study in southwest China. Mine Water Environ 39(4):902–909

Yuan S, Han G, Liang Y (2021) Groundwater control in open-pit mine with grout curtain using modified lake mud: a case study in east China. Arab J Geosci 14(12):1148

Zhang Q (2009) The south-to-north water transfer project of China: environmental implications and monitoring strategy. J Am Water Resour as 45(5):1238–1247

Zhao C, Yang J, Wang S, Zhou J, Xu F, Liu J (2021) Coupling simulation of groundwater dynamics and solute transfer in the process of deep reinjection of mine water. Coal Geol Explor 49(5):36–44 **(in Chinese, with abstract in English)**

Zhou JR, Yang TH, Zhang PH, Xu T, Wei J (2017) Formation process and mechanism of seepage channels around grout curtain from microseismic monitoring: a case study of Zhangmatun iron mine, China. Eng Geol 226:301–315