Mine Water Environ (2016) 35:294–301
DOI 10.1007/s10230-015-0352-6

TECHNICAL ARTICLE

Geothermal Water at a Coal Mine: From Risk to Resource

Qi Wang[1] · **Xinyi Wang**[2,3] · **Quanlin Hou**[1]

Received: 14 June 2014 / Accepted: 1 July 2015 / Published online: 10 July 2015

Abstract Geothermal water from a Cambrian limestone aquifer presented a flooding risk at the No. 8 coal 2_1 mine near Pingdingshan City, China. The water-bearing zones were identified using the mine transient electromagnetic method and direct current prospecting, and a groundwater drainage system was installed. After water drainage was implemented, the water level in the limestone near the haulway dropped 17.2 m in 277 days, greatly reducing the risk of a mine water inrush. The water quality, quantity, and temperature allowed it to be used for mineral baths, resulting in energy savings and emission reductions.

Keywords Water drainage · Water quality · Water quantity · Corrosivity · TEM

Introduction

Dewatering of underground mines and management of groundwater resources are important components of many mining operations, particularly coal mines. Relevant hydrologic studies on water drainage and utilization include the Winters et al. (2004) study of ground water flow parameters in a mine under confining pressures, Anandan et al. (2010) on the technology of drainage and decreasing pressure in thick confined aquifers, and Ghasemizadeh et al. (2012), who modeled groundwater transport in a karst system. Mine water may be used for domestic, industrial, and agricultural activities (Singh et al. 2010), for groundwater recharge (Sun et al. 2012), and to produce electricity (Jardón et al. 2013). He et al. (2008) and (Hancock et al. 2012) have suggested that mine water utilization be deemed of greater importance, urging effective management and comprehensive utilization of mine water during resource exploitation. The Tian'an Coal Mining Company Ltd. No. 8 Mine (hereinafter referred to as the No. 8 mine) faced the challenge of high water pressure, high ground temperature, and a water supply shortage. This paper discusses how this problem was converted into a resource.

Geography and Geology

The Pingdingshan hydrogeological unit is bounded by the Beiru River, the Sha River, Jiaxian normal fault, and the Jiulishan thrust fault (China Pingmei Shenma Group 2013), with mine adits aligned in a northwest-southeast pattern along the southwest flank of the Likou Syncline and the northeast flank of the Jiulishan fault (Fig. 1). The No. 8 mine, within the Pingdingshan unit, has operated for 33 years and is about 12 km from Pingdingshan City in Henan Province. It has an east–west extent of 12.5 km, a north–south extent of 3.36 km, and an area of about 41 km^2. There are three coal seams that could be mined; they are the 4_5, 3_9, 2_1 seams, with thicknesses of 2.0, 4.5, and 2.0 m, respectively. At present, the 2_1 coal seam is being mined at a depth exceeding 800 m, using the

Electronic supplementary material The online version of this article (doi:10.1007/s10230-015-0352-6) contains supplementary material, which is available to authorized users.

✉ Qi Wang
130001837@qq.com

[1] College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China

[2] Institute of Resources and Environment, Henan Polytechnic University, Jiaozuo 454000, China

[3] Institute of China Pingmei Shenma Group, Pingdingshan 467000, China

longwall method, and is producing 3.5 Mt/y. A main haulage roadway (which was constructed in 1981, and was too narrow to allow drilling) divides the No. 8 mine into east and west areas for 2_1 coal mining (Fig. 2).

Faulting surrounds and penetrates the No. 8 mine (Figs. 2, 3). The Likou syncline, which forms the northern border of the No. 8 mine, is a water-transmitting fault. The axis of the Likou Syncline is buried at great depth (1300–1500 m) in its central part, then gradually rises to the southeast. The No. 8 mine is also bordered on the northeast by the Huoyan normal fault, and on the south by the compresso-shear reverse fault of the No. 12 mine and the Renzhuang normal fault. The east and west part of the No. 8 mine is an artificial boundary, inside of which there are several mesoscopic structures, such as the Gaozhuang syncline, the Xindian normal fault, the Zhangwan fault, and more than 300 small high-angle normal faults with heights of 1–2 m.

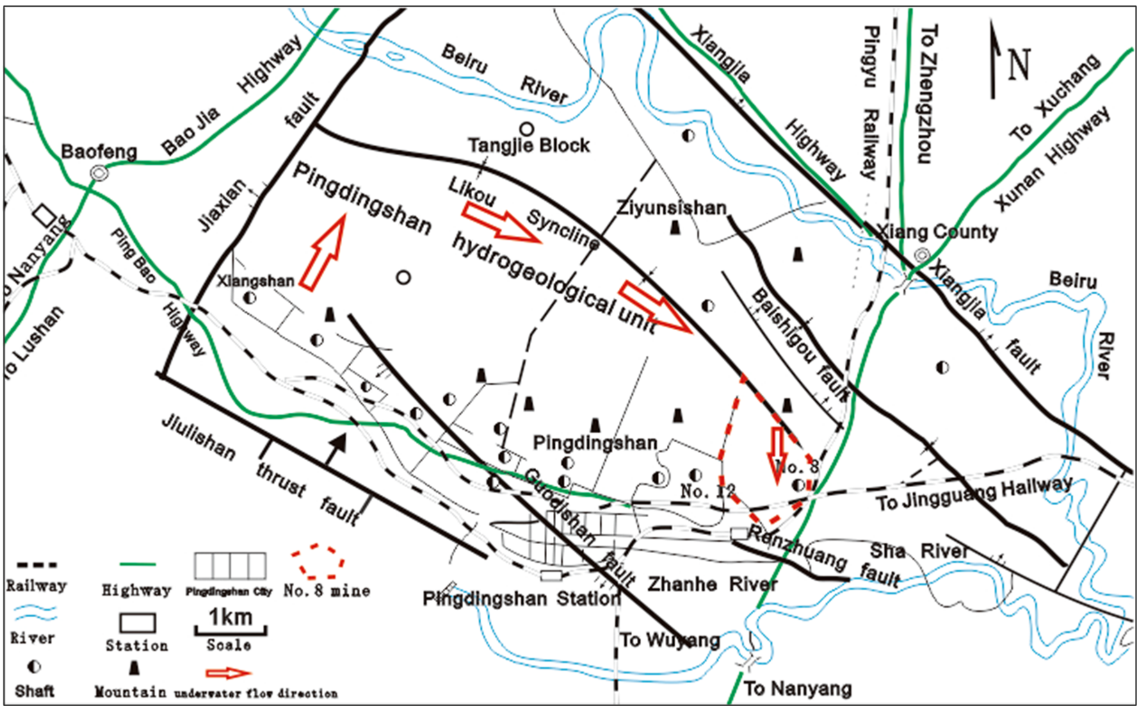

Fig. 1 Pingdingshan hydrogeological unit, mines, and transportation infrastructure (modified from China Pingmei Shenma Group 2013)

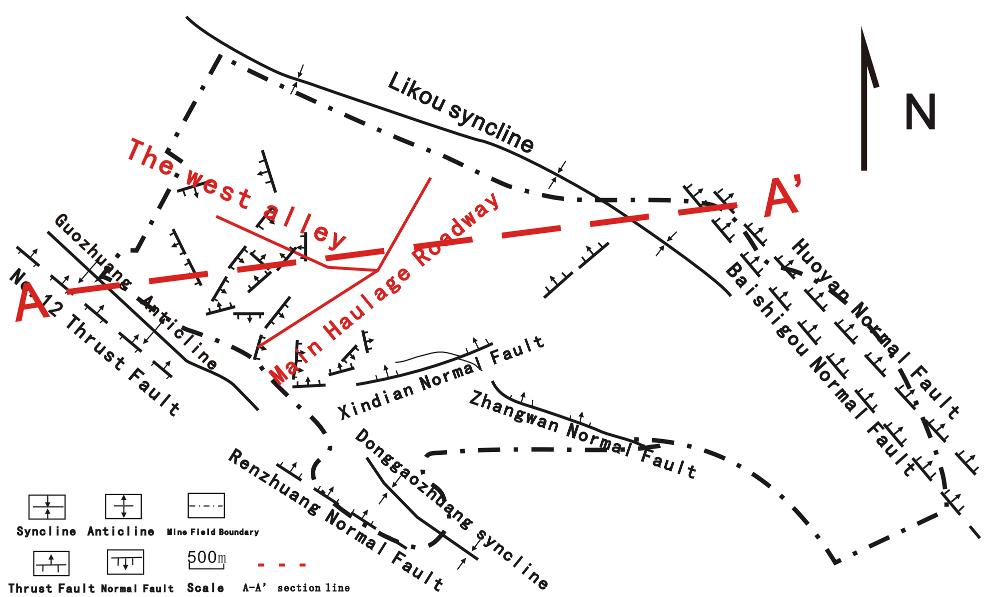

Fig. 2 Geological structure map of the No. 8 mine

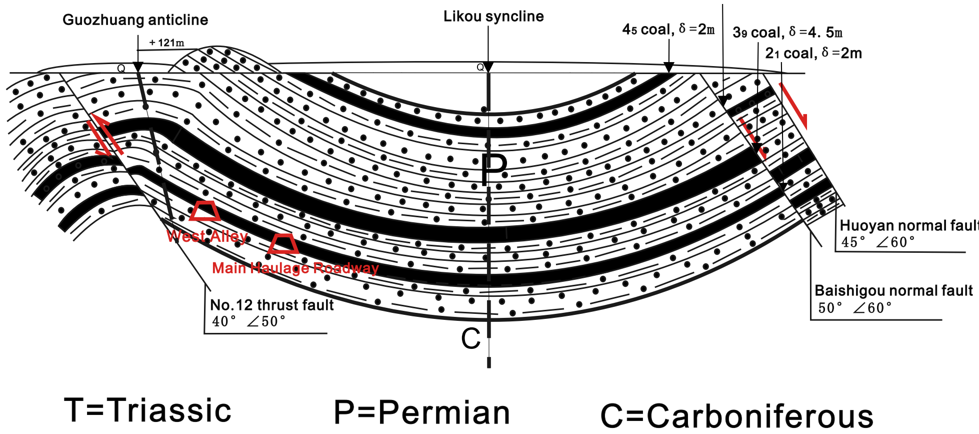

Fig. 3 Geological cross section of the A–A′ profile in Fig. 2

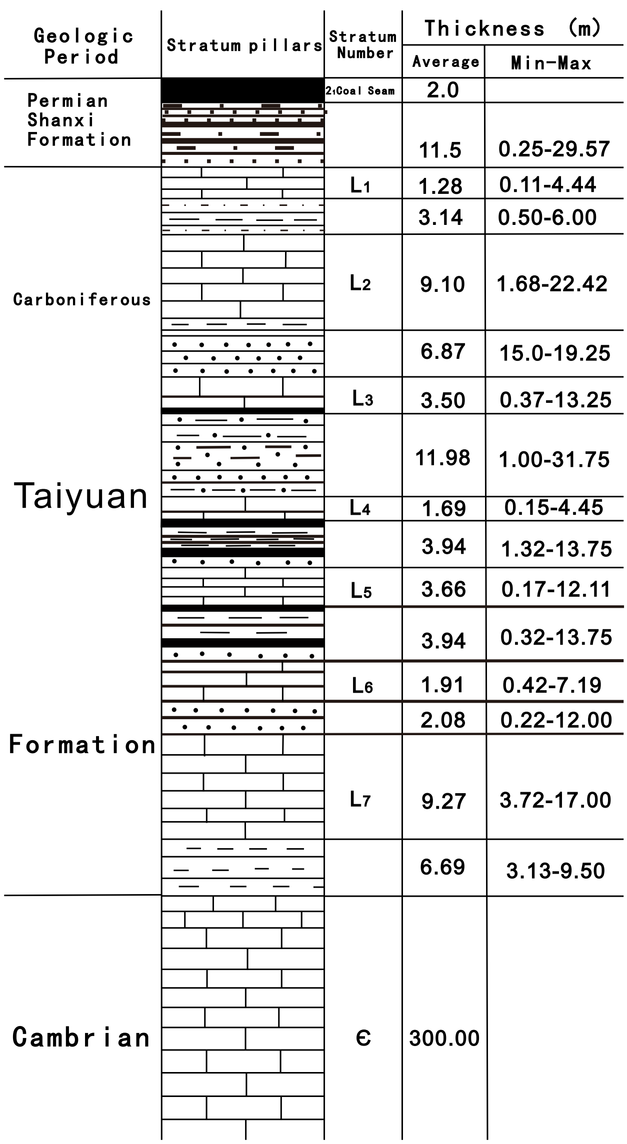

Fig. 4 Columnar schematic diagram of the underlying 2_1 coal bed (modified from China Pingmei Shenma Group 2013)

Beneath the 2_1 coal seam lays the carboniferous Taiyuan Formation limestone (layers L_1 through L_7) and Cambrian age limestone (CL) (Fig. 4); L_2, L_7, and CL all contain pressurized water that threatens safe mining operations. The distance from the top of L_2, L_7, and CL to the bottom of the 2_1 coal seam is about 16, 67, and 83 m respectively. However, the aquifer within limestone unit L_2 is not thick and does not contain a large amount of water, so it poses only a minor threat to 2_1 coal mining.

The CL is 300 m thick and spatially heterogeneous with relatively high amounts of water stored in its fracture structure. Additionally, the water is geothermal. The L_7 limestone aquifer is thinner but is hydrologically connected with the CL through the faults, so that the water tables in the two formations are basically the same. Thus, the L_7 and CL both pose a major threat to 2_1 coal mining.

An aquiclude of sandy mudstone, a coal bed, sandstone, and a thin limestone lie between the 2_1 coal seam and the CL aquifer. The thickness of the aquiclude (Fig. 5) is between 70 and 110 m, and it is thicker in the western part of the mine than in the east. The presence of the aquiclude results in a low water yield from the upper 10 m of the CL.

The Mine Water Problem

Both the 2_1 coal seam in the western portion of the No. 8 mine and the west wing haul roadway (referred to as the west alley, and built in 2005) through which the coal is transported, are at risk of flooding. The elevation of the 2_1 coal is −690 to −800 m, while the water level elevation of the L_7 and CL aquifer is about—300 m (In China, the ±0 datum is the average sea level elevation of the Yellow Sea), so that the hydraulic pressure at the mining working face is 4.35-5.40 Mpa. The distance from the top of L_7 to the bottom of the 2_1 coal is only 67 m. The 2900 m long west alley lies about 3 m beneath the bottom of the coal seam,

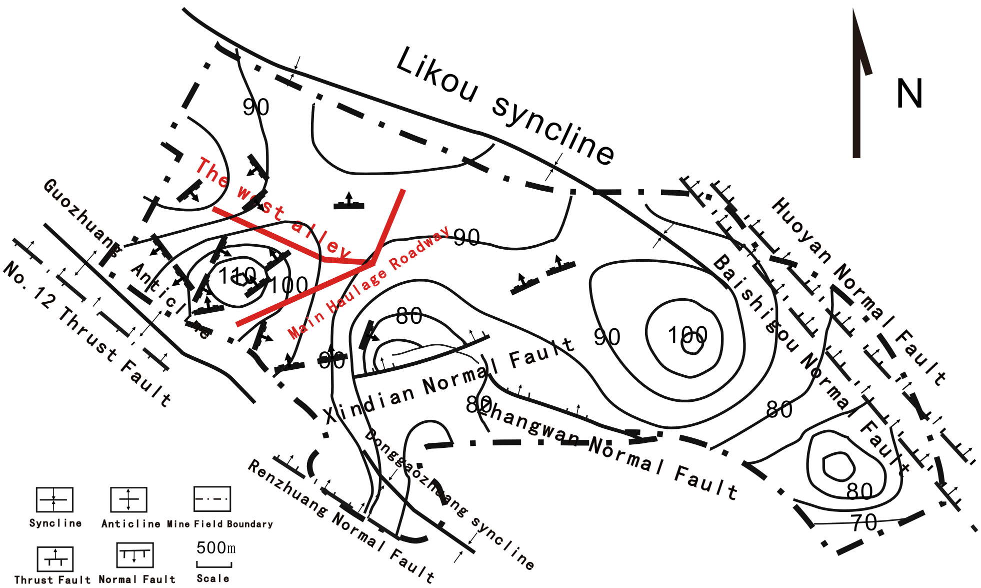

Fig. 5 *Contour map* of the aquiclude thickness between the *bottom* of the 2_1 coal and the *top* of the CL

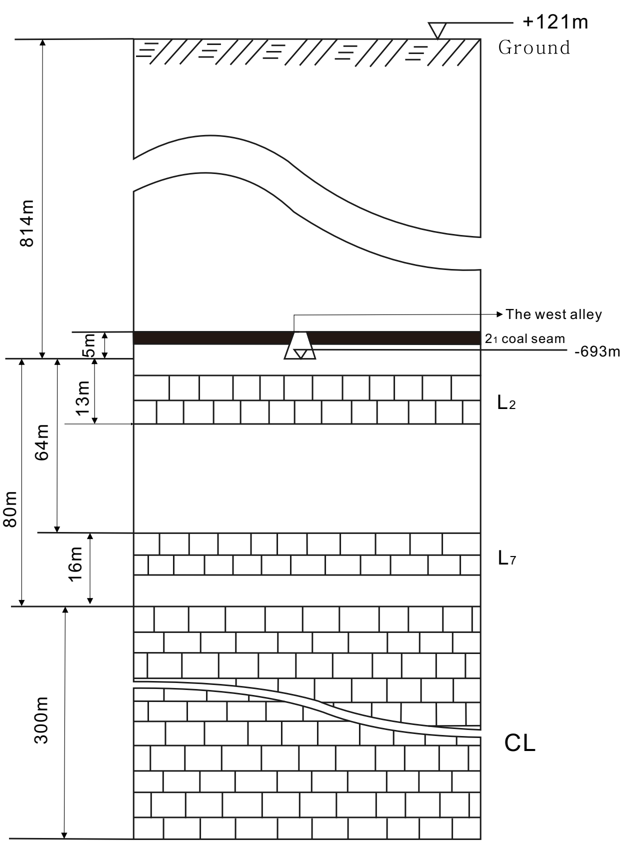

Fig. 6 Diagram of distance from the west alley to the Cambrian age limestone (CL)

so the L_7 is, on average, 64 m below the floor of the west alley (Fig. 6). Given the hydraulic pressure and the short separation distance, there is a risk of a potentially hazardous inrush of water from the L_7 and CL aquifer (State Administration of Worker Safety 2009; Wang et al. 2011).

Additionally, when mining the 2_1 coal at an elevation of −690 m, the temperature of some working faces exceeds 36 °C. This affects the physical and mental health of workers, which in turn affects labor efficiency and increases the cost of mining (Chai 2010; He et al. 2011; Tan et al. 2009; Yang et al. 2011). Twelve holes, with depths of 90–95 m (i.e. 10–15 m into the CL), were drilled at a uniform spacing in the west alley from 2006 to 2007. Three holes had a water inflow of 3 m^3/h with a water temperature of 45 °C. No water flowed from the other nine holes, indicating that the upper 10 m of the CL (an oolitic limestone) has low permeability or storativity where these holes are located.

Constraints on Geothermal Water Movement

Karst Development

Drilling data showed that when the buried depth of the CL was <420 m, the CL has well-developed karst fissures, and the water flow per unit is 2.27–26.62 L/(s m). When the buried depth of the CL was >420 m, the karst fissures are weakly developed. However, the dissolution pores, solution fissures, and karst fissure of the CL are only well developed where structures are intensively developed and at the junction of the fault.); the water flow per unit is 0.00203–0.894 L/(s m), The buried depth of the CL in the west wing exceeds 890 m, so the karst fissures are weakly developed, and the water-bearing properties are generally poor relative to other areas. Thus it is important to determine the karst development zone for groundwater drainage in areas of the CL.

Groundwater Flow

The supply and flow of CL geothermal water is controlled by large structures and the water-bearing zone is controlled by small and medium-sized structures in the mining area. Because faults (the Jiulishan thrust, Jiaxian normal fault, and Guodishan normal fault) act as barriers to groundwater flow, CL groundwater is recharged only by atmospheric precipitation at the emergence zone south of the Xiangshan Mine (Fig. 1). It then flows to the northeast west of the Pingdingshan unit, but when it reaches the Likou syncline, it becomes heated and flows in a southeast direction. The geothermal water in the central part of the Likou syncline has the highest temperature (Chai 2010).

The water level elevation for the CL below the No. 8 mine is −230 to −380 m, averaging about −300 m (Fig. 7). Geothermal water from the Likou syncline migrates from the north to the south (Fig. 1), so the Likou syncline supplies geothermal water to the No. 8 mine.

Due to the convergence lift effect of the Likou syncline and the Baishigou normal fault acting as a barrier to flow, geothermal water level in the CL increases gradually, reaching its greatest height at the end of the Likou syncline, where the flow direction changes from north to south, ultimately flowing towards the No. 8 mine. The intensive distribution of small and medium-sized permeable structures contributes to the aggregation of geothermal water. The reverse fault of the No. 12 mine and the Renzhuang normal fault hinder the southerly migration of the geothermal water, thus forming a CL groundwater enrichment region beneath the No. 8 mine.

Geothermal Gradient

At a depth of 25 m, regional groundwater has a constant temperature of 17.2 °C (Henan Polytechnic University 2010). Using water temperature monitoring data and the water inflow position, the geothermal gradient of the CL aquifer can be calculated:

$$\theta = 100 \times (t - t_0)/(Z - Z_0) \quad (1)$$

where θ is the geothermal gradient, °C/100 m; t_0 is the temperature of constant temperature zone (17.2 °C); Z_0 is the depth of the constant temperature zone (25 m); t is the water temperature of the drill hole or groundwater, °C, and; Z is the average buried depth of the drilling hole or groundwater flow, m. The geothermal gradient is calculated as shown in supplemental Table 1; the isocline of the geothermal gradient is shown in supplemental Fig. 1. Supplemental files accompany the on-line version of this paper and can be downloaded for free.

The geothermal temperature gradient of CL groundwater is between 3.55 and 4.35 °C/100 m, with an average value of 3.9 °C/100 m, which indicates an unusually high temperature zone. The geothermal gradient near the Likou syncline is the lowest, while the geothermal gradient near the southern border is the greatest, illustrating that a lower geothermal gradient results when there is a greater groundwater velocity, and a higher geothermal gradient occurs when the groundwater velocity is less. The largest region of the geothermal gradient is located in a zone consisting of several medium-sized structures, such as the Xindian normal fault, Donggaozhuang syncline, and

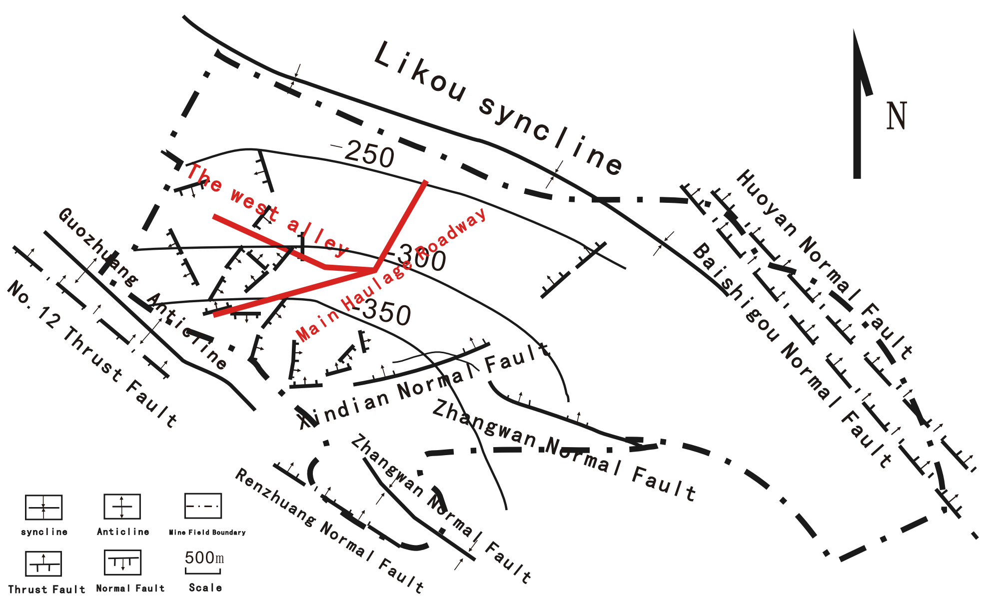

Fig. 7 *Contour map* of the CL water level of May, 2008 in the No. 8 mine

Zhangwan normal fault, indicating that larger structures can greatly influence the temperature distribution of a geothermal field.

Detection of the Water Anomaly Area

If water was to be drained to reduce the threat of inrush and reduce the temperature at the working face, it was clear that the drainage holes should be placed at locations where they could be constructed inexpensively and where they could remain operational without impeding mining operations. The west alley was a favorable zone for the drainage holes because it is a permanent roadway and because it is wide enough for the drilling holes. Environmental disturbance was reduced by using geophysical methods. Permissible transient electromagnetic exploration (TEM) and the direct current (DC) method (Han et al. 2010; Henan Polytechnic University 2009; Su et al. 2011) were conducted along 2320 m of the west alley, from east to west, to detect the storativity of the CL with a probing depth of 80–150 m. The dot spacing of the TEM survey was 10 m, with physical points measured at 233 locations and reviewed points for 62. The dot spacing of the DC survey was 60 m, the maximum polar distance was 140 m, and 260 physical points were measured (55 points were reviewed).

The apparent resistivity of the west alley TEM for CL was 1–105 Ω m; resistivity <5 Ω m was deemed as lower resistivity anomaly areas. The apparent resistivity detected for the same areas using DC was ≈100–2100 Ω m; resistivity <400 Ω m was designated as lower resistivity anomaly areas. The comprehensive exploration results of TEM and DC are shown in supplemental Figures 2 and 3.

As shown in supplemental Figure 2, the lower resistivity anomaly areas exist directly below the west alley at 140–210, 330–385, 505–588, 690–760, 815–865, 1300–1400, and 1998–2060 m, from east to west. The amplitude of variation of the apparent resistivity (the DC method) was greater. All of these could contain lower resistivity CL areas, indicating anomalously wet zones with well-developed fractures in them.

Geothermal Water Drainage

Layout of the Drainage Holes

The radius of influence (ROI) of a CL aquifer drainage hole can be calculated using an empirical formula:

$$R = 10 * S * \sqrt{K} \quad (2)$$

where K is the permeability coefficient, m/d; S is the drainage step-down hydraulic head value, m; and R is the calculated ROI value of the aquifer drainage step-down hole, m.The safe operating water pressure of a floor aquiclude can be calculated using the following empirical formula:

$$P = M * T_S \quad (3)$$

where P is the safe operating water pressure of floor aquiclude, MPa; M is the effective aquiclude thickness of 2_1 coal floor, m; and Ts is the critical water bursting coefficient, MPa/m.

The permeability coefficient of the CL aquifer near the west alley is 0.01313 m/day, which was calculated using data from the pumping test (Henan Polytechnic University 2012). The water level elevation in the CL is about −301 m, the top elevation of the CL is about −773 m, and the water pressure of the 2_1 coal is 4.5 Mpa (i.e. 472 m). The 2_1 coal seam is 83 m above the top of the CL, the thickness of the damaged floor aquiclude (which is destroyed during mining) is 20 m, and the effective aquiclude thickness of the 2_1 coal floor is 63 m. The small faults near the west alley are well developed, with a critical water bursting coefficient of 0.06 MPa/m (Wang et al. 2011; State Administration of Worker Safety 2009). The safe operating water pressure for 2_1 coal floor of 3.78 MPa (i.e. 397 m) was obtained by Eq. 3, and the drainage step-down hydraulic head value is 75 m. A ROI of the CL aquifer at 86 m was obtained using Eq. 2, meaning that the distance between each drainage hole should be no <172 m to efficiently achieve the desired water pressure decrease. Seven drainage holes were drilled at locations of 160, 350, 560, 740, 855, 1320, and 2010 m from east to the west of the alley.

Vertical Structure of the Drainage Holes

The diameter of the drainage holes was designed to ensure that water could be drained for a depth of 150 m. For a drilling depth of 0–90 m, the required diameter of the shaft is 216 mm; at a depth of 90–150 m (i.e. 10–70 m into the CL), the diameter must be 152 mm. Damage caused by terrain deformation associated with mining was avoided by using sleeving with a diameter of 175 mm in the upper (0–90 m) section.

Using the Cambrian Geothermal Water Resource

Water Quality Evaluation

According to the comprehensive study results above, seven drainage holes were designed and built in the west alley in 2012. Each yielded water, with a total yield of about 300 m^3/h and a geothermal water temperature of 50 °C (Henan Polytechnic University 2012). Comparing results of the drill holes built in 2012 with those built in 2006–2007, extending the drilled depth further than 10 m into the CL provided greater flow yields. This is because the upper 10 m of the CL is oolitic limestone, below which is layered limestone, with better hydraulic properties.

Water requirements for mine operation (except drinking water) are 1996 m^3/day in winter and 1950 m^3/day the rest of the year. Depending on water quality, the geothermal water could be used for miner's showers, winter heating, mine operations, and medicinal hot baths. Water samples were collected in 2008, 2009, 2012, and 2013. Analysis showed that the: (1) hydrochemical type is $HCO_3 \cdot SO_4$-Na·Ca; (2) fluorine (1.32 mg/L), total α content (2.06 Bq/L), and the ^{226}Ra content (1.98 Bq/L) exceed the national standard (Standards for Drinking Water of China 2006; Standards for Natural Mineral Water of China 1995), so it should not be used as drinking or mineral water, and; (3) metasilicic acid (31.2 mg/L) and fluorine content (1.32 mg/L) meet the medicinal value standard (Geologic Exploration Standard of Geothermal Resources of China 1989).

Water Transport and Distribution Engineering

The geothermal water production capacity of the west alley drainage system is 300 m^3/h (7200 m^3/day), which would meet the maximum daily domestic water consumption of the No. 8 mine in winter (4225 m^3/day), and could also meet its maximum hourly domestic water consumption (268 m^3/h) (Henan Polytechnic University 2012). The potential for corrosion and scaling of pipes, equipment, and valves in a water transport system was evaluated using the Larson Index method:

$$LI = \left(\gamma_{CL} + \gamma_{SO_4}\right)/ALK \qquad (4)$$

where γ_{CL} and γ_{SO_4} in Eq. 4 represent the chloride and sulfate ion content, in mg/L, and ALK is the total alkalinity, in mg/L as $CaCO_3$. The chloride ion content of the geothermal water in the No. 8 coal mine is 54 mg/L, the sulfate ion content is 179 mg/L, the total alkalinity is 311 mg/L, and the Larson Index was calculated as 0.75. The geothermal water would be mildly corrosive to the iron piping, but would not cause scaling. A water transport and distribution system was designed from the west alley to the ground surface in order to facilitate water supply and demand (supplemental Fig. 4).

Results

After the seven drainage holes in the west alley were drilled, a water distribution system was set up for geothermal water utilization of the No. 8 mine. The geothermal water replaced water that was being used for showers (13,000 miners and 15,000 residents), winter heating of ground buildings, and mining operations. With utilization of geothermal water, the four coal-fired boilers (which were needed to meet the hot-water supply needs) completely stopped running in spring, summer, and autumn. In winter, only two boilers are required. This saved coal (14,256 t/y) and electricity (648,000 kWh/y). Mine drainage disposal fees were reduced, adding up to a total savings of $1.85 million/y. Significantly reducing coal use also lowered air emissions: particulates were reduced by about 80.5 metric tons (t)/y, SO_2 by 697.4 t/y, CO by 304 t/y, and NO_2 by about 54 t/y. Coal ash production was also reduced by about 4292 t/y.

Drainage decreased the temperature of the mine roadways and working environment, and reduced the water inrush threat in the 2_1 coal mining area. Water level monitoring data showed that as the 300 m^3/h of pressurized water from the seven drainage holes was captured and distributed for use, the CL water level under the west alley dropped 17.2 m in 277 days. Although this did not eliminate the high water pressure, it did reduce the threat of mine water inrush in the west alley.

Conclusions

Geothermal water lies below the No. 8 mine, in the CL aquifer, creating high temperatures along the working face and posing a threat of flooded mine workings. The supply and flow of geothermal water is controlled by macrostructures, and its concentration is determined by the distribution of small and medium-sized voids and fractures. The geothermal anomaly zone and water-bearing zones of the CL were determined by studying the geology, hydrogeology, and ground temperature characteristics, and by underground geophysical surveys.

The spacing of drill holes in the west alley was determined by the results of geophysical surveys. Seven drainage holes placed at least 172 m apart, penetrating 10–70 m into the CL, yielded 300 m^3/h with a water temperature of 50 °C. The CL water level dropped 17.2 m in 277 days, reducing the mine water inrush threat in the west areas and the main haulage roadway.

The water quality was tested to determine the best way to use this new water resource and although it cannot be used for drinking, it can be used in boilers and for residential mineral baths. The geothermal water is mildly corrosive to the iron water conveyance system, but does not cause scaling. Remarkable economic and environmental benefits were achieved after the drainage holes and water conveyance system were installed to make use of the geothermal water that had formerly endangered mine operations and worker health.

Acknowledgments This work was financially supported by the National Natural Science Foundation of China (Grant 41272250) and Henan Province's Technological Innovation Team of Colleges and Universities (Grant 15IRTSTHN027).

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