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ORIGINAL ARTICLE

Coordinated exploitation of both coal and deep groundwater resources

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Abstract

Throughout China, both coal and water are very important resources; however, serious conflict can arise between mining of deep coal reserves and essential aquifer resources. The problem is particularly severe in eastern China where a deep, thick, and productive Ordovician limestone aquifer immediately underlies Permo-Carboniferous coal-bearing sediments and poses a serious threat to the safety of coal exploitation. The problems are caused by high water pressures in the Ordovician aquifer and the risk of catastrophic flooding at the coalface caused by strong upward flow across a relatively thin aquitard. The problem can be alleviated by mine dewatering, but this generates large volumes of contaminated wastewater that require safe disposal. In a feasibility study carried out at Yanzhou coalfield, eastern China, hydrogeological studies have been undertaken to explore options for utilizing water pumped during mining operations, thus making more efficient use of the Ordovician groundwater reserves. The groundwaters are recharged at outcrops but readily become SO_4·Cl–Ca·Mg in character with TDS increasing considerably with depth. Focusing on the Xinglongzhuang coal mine, test pumping and development of a transient groundwater flow model of the system have allowed alternative strategies for pressure management to be investigated. The study shows that coal-mining operations can proceed safely with as few as six underground dewatering boreholes removing 1800 m^3/h. Moreover, the extracted water could be utilized after treatment to reduce sulfate concentrations. The coordinated exploitation approach demonstrated in this study provides a good example of wise environmental stewardship that other extractive industries would do well to consider.

Keywords Deep aquifer resources · Deep coal mining · Hydrochemistry · Aquifer modeling · Mine drainage

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Introduction

Throughout China, groundwater is often the preferred source of water supply as it tends to be more reliable and economical than surface water, and more resilient to pollution. Meanwhile, the exploitation of coal is crucially important to the Chinese economy, accounting for 61.8% of the country's primary energy consumption in 2016, and expected to remain at similar levels until at least 2020. Unfortunately, coal mining and groundwater resource management frequently come into conflict with the detrimental effects of coal mining on water resources well documented globally (Jarvis and Younger 2000; Kallioras and Ružinski 2011; Johnson and Younger 2006). A primary issue relates to mine safety, the potential inrush of groundwater at the working face or tunnel face during the mining of deep coal seams posing a serious threat to both miners and their operations (Zhang 2005). Pumping can alleviate this risk, but this can lead to many secondary issues such as land subsidence, mine collapse, and the unnatural inducement of water from neighboring water-resource aquifers and even the surface (Unlu et al. 2013; Salmi et al. 2017; Qiao et al. 2017). The problems can be particularly severe with deep coal mining as high-pressure differentials across thin aquitards can lead to rock burst and high-pressure-water inrush (Wu et al. 2014; Sun et al. 2016; Qiao et al. 2014; Kang et al. 2015; Holub et al. 2011). China has a long history of mining disasters and is well aware of the dangers, but given that the Chinese economy is highly dependent on its coal resources, the challenge has been to develop ways of mitigating and managing risk while ensuring that coal production targets are maintained.

The control of water inrush during deep coal-seam mining is particularly difficult in eastern China where rich coal-bearing strata are narrowly separated from an underlying fractured and locally karstified limestone aquifer of Ordovician age, an important groundwater resource with a thickness in the range 500–800 m. The risks are becoming increasingly severe as coal-mining proceeds to deeper horizons and the vertical separation between the coalface and high-pressure zones in the underlying aquifer becomes reduced. The threat of water inrush is well recognized and is normally controlled by one of two methods: draining depressurization and chemical grouting. Grouting the uppermost 10 m of the Ordovician can be effective locally, but is extremely difficult to perform reliably at a large scale given the rock's highly heterogeneous weathering. Chemical grouts can also lead to water pollution. Draining depressurization is more dependable, but diverts to waste considerable amounts of potentially useful water (Wu et al. 2000). Moreover, if water extracted during mine dewatering is poor in quality and is discharged without adequate management and treatment, it may cause significant damage to the local environment.

Efforts to control the inrush of water are exacerbated locally by unusually high water pressures in the Ordovician aquifer (as high as 4–12 MPa). Given that the aquitard separating these high-pressure zones and the coalface and tunnels is typically 10–50 m thick, the threat of break-through is immense. In all cases, the viability of coal extraction must be methodically evaluated in terms of the risk and the costs of mitigating the risk, and dewatering methodologies are a key part of the cost–benefit–risk analysis. Due to their relatively low cost, underground dewatering wells installed close to the coal-mining workface would normally be preferred over deep boreholes drilled from surface. This allows the water to be collected in specially designed tunnels and conveyed for treatment, thus reducing the risk of acid coalmine drainage being discharged at the surface and contaminating the environment (Skousen et al. 2017; Tiwari et al. 2017). To maintain safe conditions and perform effectively, it is essential that the flow hydraulics and hydrochemistry of the local dewatering system be understood in considerable detail (Osenbrück et al. 2006; Mahlknecht et al. 2004; Huang et al. 2017; Heidari-Nejad et al. 2017).

This paper presents, as a case study, the work undertaken to assess the feasibility of dewatering options at Xinglongzhuang coal mine, part of the Yanzhou coal field in Shandong Province, eastern China. The investigation of deep karst (burial depth is about 450–750 m) has great difficulty and great economic costs. 97 precious boreholes were used to reveal the hydrogeological conditions of deep karst aquifer and to try to exploit both coal and deep groundwater resources. This paper describes (1) the hydrogeology/hydraulics of the Ordovician karst aquifer system, (2) the groundwater hydrochemistry, (3) the hydraulic field testing that led to the development of a groundwater flow model used to support decision-making, and (4) a feasibility assessment that includes the best option for water management. The work presented here is consistent with the Chinese government's "three deep exploitations" scientific research strategy involving deep space, deep sea, and deep earth. It focuses on deep water during mining of deep coal resources and provides an important example of coordinated multi-resource exploitation and development.

Study area

The study focuses on the Xinglongzhuang coal mine, part of the Yanzhou coal field in Shandong Province, eastern China. It is one of the five mines operated locally by the Yankuang Group Corporation, others being the Yangcun, Baodian, Dongtan, and Nantun coal mines (Fig. 1). The surface of the study area is represented by a relatively flat, Quaternary alluvial plane occupying an elevation of between 44 and

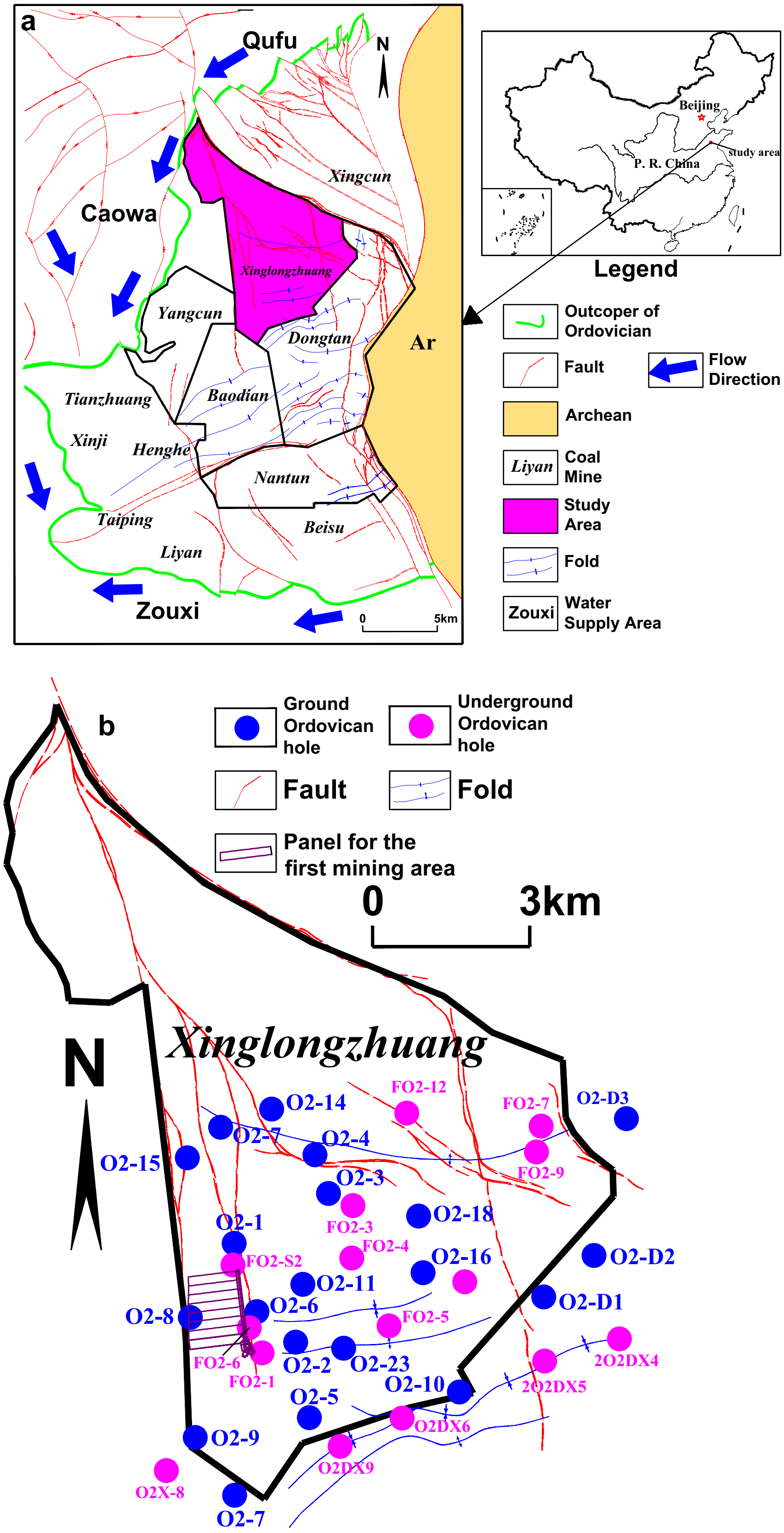


Fig. 1 **a** The study area and location of the Xlzh coal mine; **b** The Xinglongzhuang coal mine and sites of exploratory holes penetrating the Ordovician limestone aquifer

52 m above sea level (masl). Below the alluvium, Mesozoic and Paleozoic sedimentary formations form a shallow syncline (limb dip angles of < 10°) that plunges gently towards the southeast (Fig. 2). The Yishan fault separates these formations from the Archean basement that outcrops in the east. Fractured, locally karstified, Ordovician limestones and

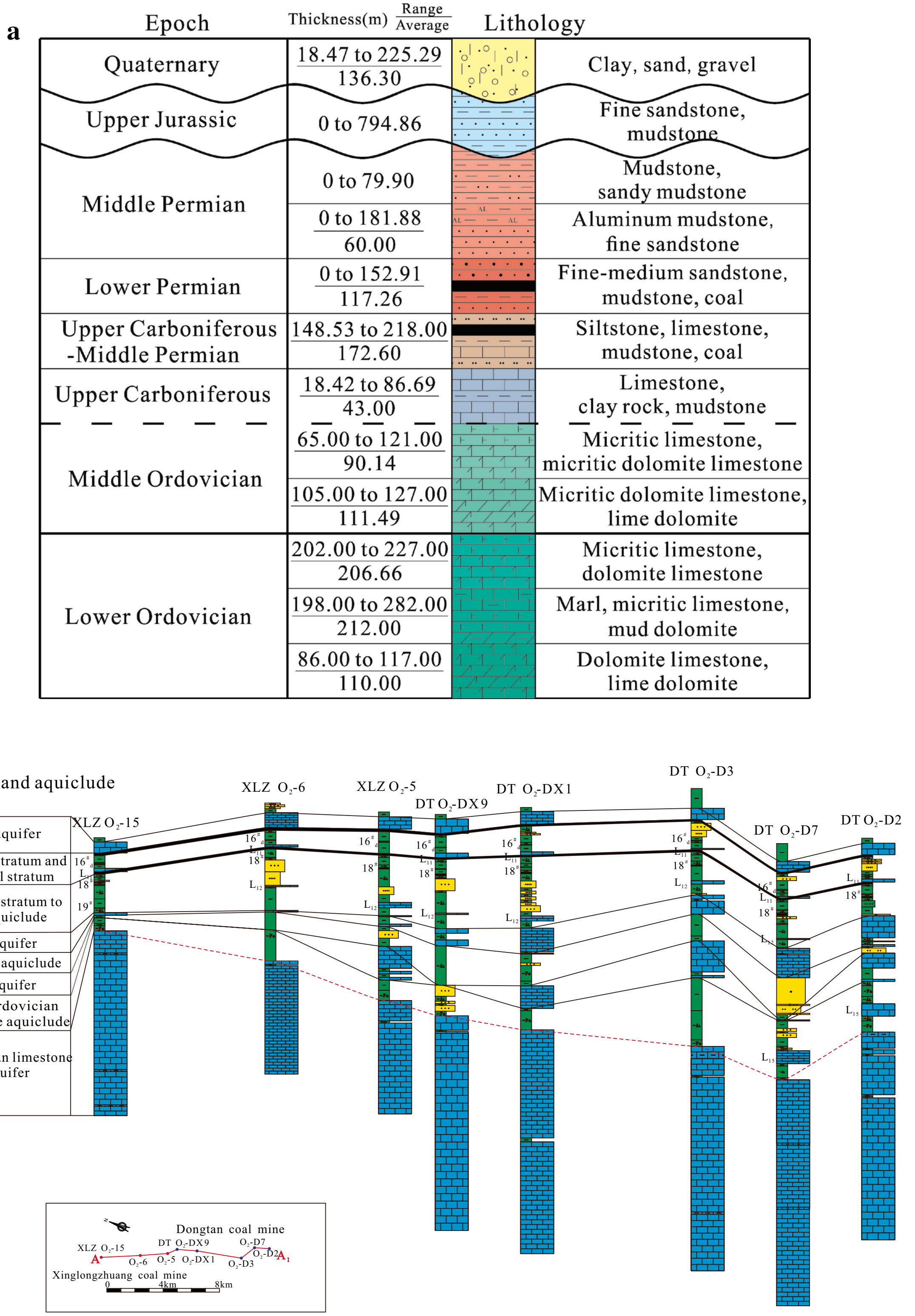


Fig. 2 Formation of study area: **a** Stratigraphic column of study area; **b** a well cross section of study area, XLZ is Xinglongzhuang, and DT is Dongtan for simplification

dolomites are exposed in the northwest and southwest, areas that support the primary water-supply wellfields (Qufu, Caowa, and Zouxi) (Fig. 1a). More centrally, the carbonate aquifer system lies beneath the Mesozoic sediments that host the coal reserves.

In total, the Ordovician aquifer system covers an area of 1373 km^2. The karst is exposed over an area of 181 km^2 and lies buried beneath the Yanzhou coal field over an area of 420 km^2. Average annual precipitation is 714 mm and the mean annual air temperature is 14.4 °C.

The Xinglongzhuang coal mine has an area of 57.7 km^2. Until recently, mining operations focused on the coal seam No. 3 which was approved for the production of approximately 7 million tonnes in 2007. These reserves have now been depleted and attention has turned to deeper reserves at coal seams Nos. 16 and 17. These coal seams lie much closer to high-pressure zones in the underlying aquifer and are, therefore, attracting considerable hydrogeological interest. The first proposed mining area is shown in Fig. 1b. The "ground Ordovician hole" is the borehole which starts to be drilled on the surface or ground. And the "underground Ordovician hole" is carried out from the floor of the underground tunnel/roadway.

Hydrogeology and engineering geology

The full sedimentary sequence for the study area is shown in Fig. 2. Aquifers that could negatively influence coal-mining operations in the area would normally include:

- the thick-bedded Ordovician karst aquifer,
- relatively thin Carboniferous karst aquifers,
- overlying aquifers in the Jurassic sandstones, Permian sandstones, and surficial sands and gravels of the Quaternary.

In terms of the Xinglongzhuang coal mine, the focus of this study, carbonates of Carboniferous are generally absent, and only aquifers of the Ordovician (total thickness from 500 to 550 m) are considered to be a potential threat. Closest to coal seams Nos. 16 and 17, and of greatest concern, are limestones and dolomites of the Badou group. These have a mean thickness of around 100 m and are considered to be hydraulically isolated from deeper Ordovician aquifers. Consequently, drilling and testing focused on this aquifer system.

Carbonates of the Middle Ordovician Badou group are shown in outcrop and in drilling cores in Fig. 3. They generally comprise grey limestones or grey dolomites with a massive, compact structure. Fracturing is common both at outcrop (Fig. 3a) and in drill cores (Fig. 3b and c). The degree of fracturing in drill cores ranges from 2.58 to 8.53%; some fractures are infilled with calcite. Rock Quality Designation (RQD) is used as a classification parameter. This quantitative index is a modified core-recovery percentage which incorporates only those pieces of core that are 100 mm or greater in length (Deere and Deere 1988). The RQD of drilling cores generally lies between 10 and 90%, the lowest values associated with fractured sections (Fig. 3b). Measured values of

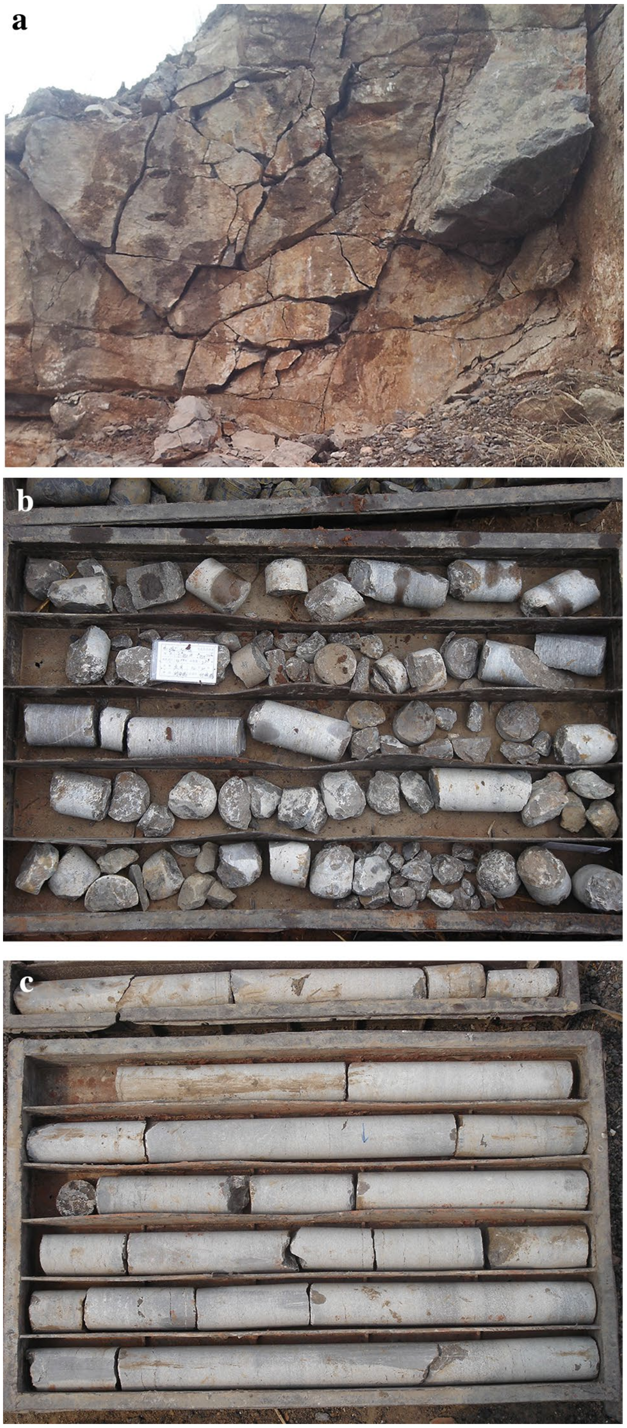


Fig. 3 The Badou Group of the Middle Ordovician: **a** in outcrop; **b** intensively fractured drilling cores: depth of 853.22 m-858.83 m; **c** largely intact drilling cores: depth of 1102.54–1107.54 m

uniaxial compressive strength range from 80 to 150 MPa and Poisson ratios are less than or equal to 0.17. These indicate the characteristic of high strength and brittleness.

Drilling investigations reveal that Badou group is separated from the targeted coal seams by an aquitard in the lowermost coal measure strata. The aquitard mostly comprises a lower layer of thick gray limestone, with some brecciated limestone and yellow–green marl, and an upper layer consisting of gray or dark gray thick-bedded limestone and dolomitic limestone with thin-bedded limestone. For coal seam No. 16, the thickness of the aquitard ranges from 34.04 to 79.01 m with an average of 56.61 m (Fig. 4). For coal seam No. 17, the thickness of the aquitard ranges from 25.59 to 67.60 m with an average of 47.28 m (Fig. 4).

Groundwater flows in a generally southerly direction across the study area according to long-term water level observation data of local water-supply stations and Qiao et al. (2014). The aquifer is fed at outcrop in the west and initially flows east into the basin before moving in the direction of Dushan Lake, just to the south of the study area. The primary concern is the presence of water pressures in the Ordovician limestone aquifer that range from 4 to 12 MPa beneath the Yanzhou coalfield as a whole and from 4.5 to 8 MPa immediately beneath the Xinglongzhuang coal mine (Fig. 5). These pressures generate vertical hydraulic gradients across the intervening aquitard (metres of water head per metre distance) that locally exceed 200 or more. The fear is that such extraordinarily high gradients may lead to significant flows through the aquitard, even under conditions of very low hydraulic conductivity (0.01–0.1 m/d). Where the hydraulic conductivity of the aquitard is enhanced by fractures, flows through the aquitard could lead to very rapid and severe flooding of the coalface and mine workings as the excavation proceeds.

Hydrochemical and hydraulic investigations

At the present time, 97 boreholes have been drilled to explore the geological, hydraulic, and hydrochemical characteristics of the Ordovician karst aquifer Fig. 5. These boreholes include ground holes and underground holes. All the constructed Ordovician holes were drilled 100 m into Ordovician aquifer. Before the boreholes reached the top surface of Ordovician aquifer, the casing must be focused for isolating other aquifers above Ordovician, and then, the boreholes were drilled about 100 m into Ordovician. The section in Ordovician is bare hole. For the present study, water samples were collected from 74 of these boreholes for hydrochemical

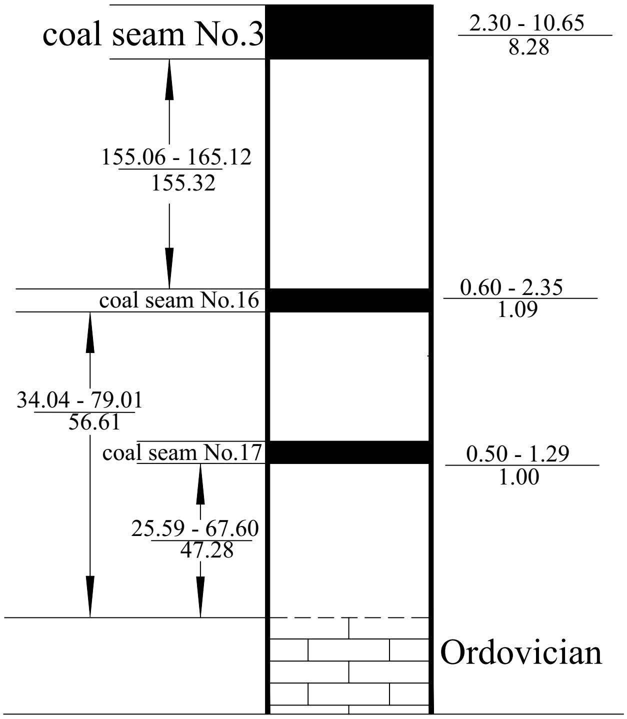


Fig. 4 Intervals between the top of the Ordovician and coal seams shown as ranges and as averages (metres)

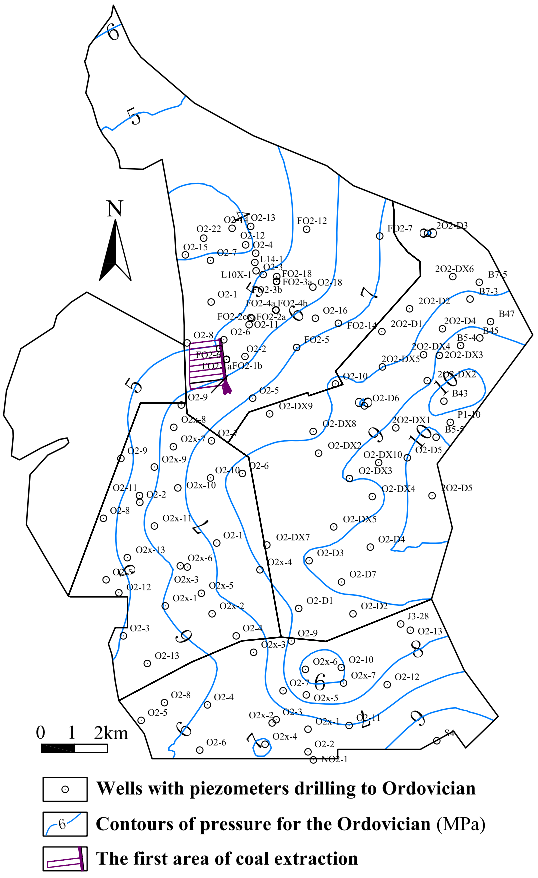


Fig. 5 Contours of pressure for the Ordovician limestone (MPa) in the region of the Yanzhou coal field operated by the Yankuang Group. 1 MPa is equivalent to 102 m head of water

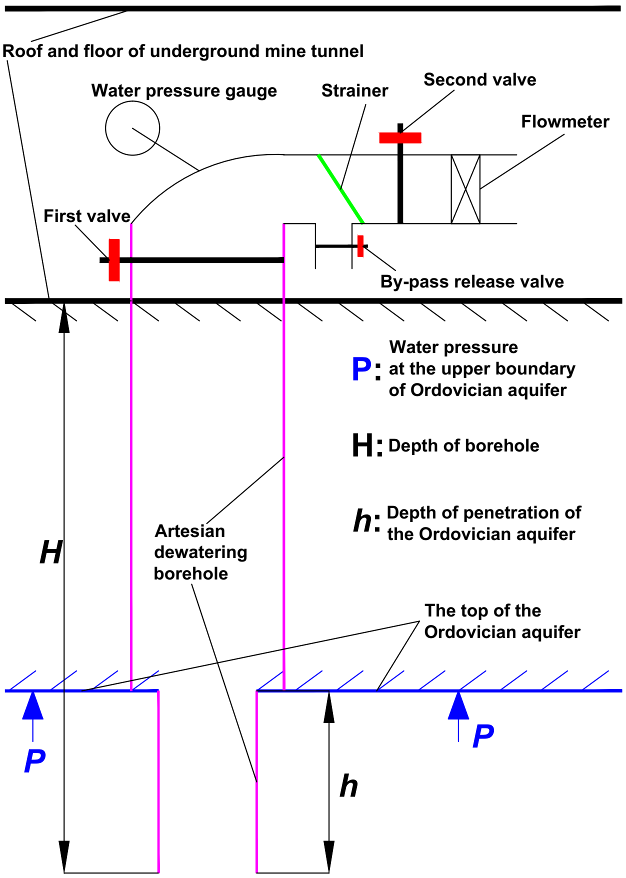


Fig. 6 Sketch map showing the arrangement for testing the highly pressurized boreholes

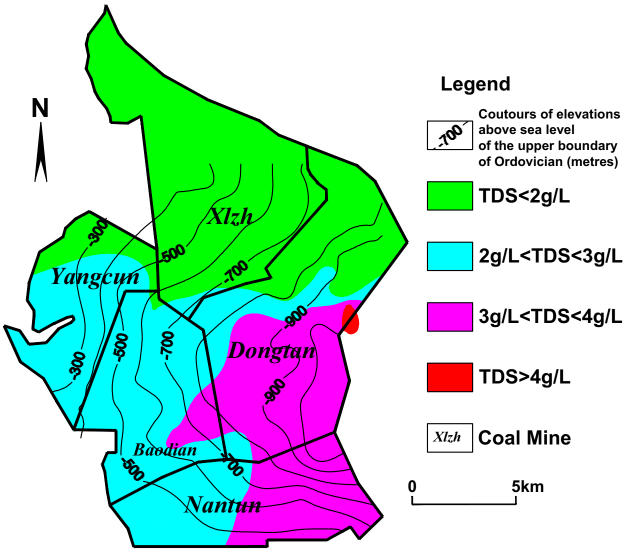


Fig. 7 Total Dissolved Solids (TDS) in Ordovician limestone groundwaters immediately beneath the five Yanzhou coalfield mines operated by the Yankuang Group

chemical analysis. Analyses were performed in the laboratory of the Geological Engineering Survey Institute of South Shandong using standard procedures recommended by Chinese Ministry of Land and Resources (CMLR). Parameters determined included pH, major cations and anions, and total dissolved solids (TDS). Stable isotopic compositions were also conducted for selected samples using a Finnigan

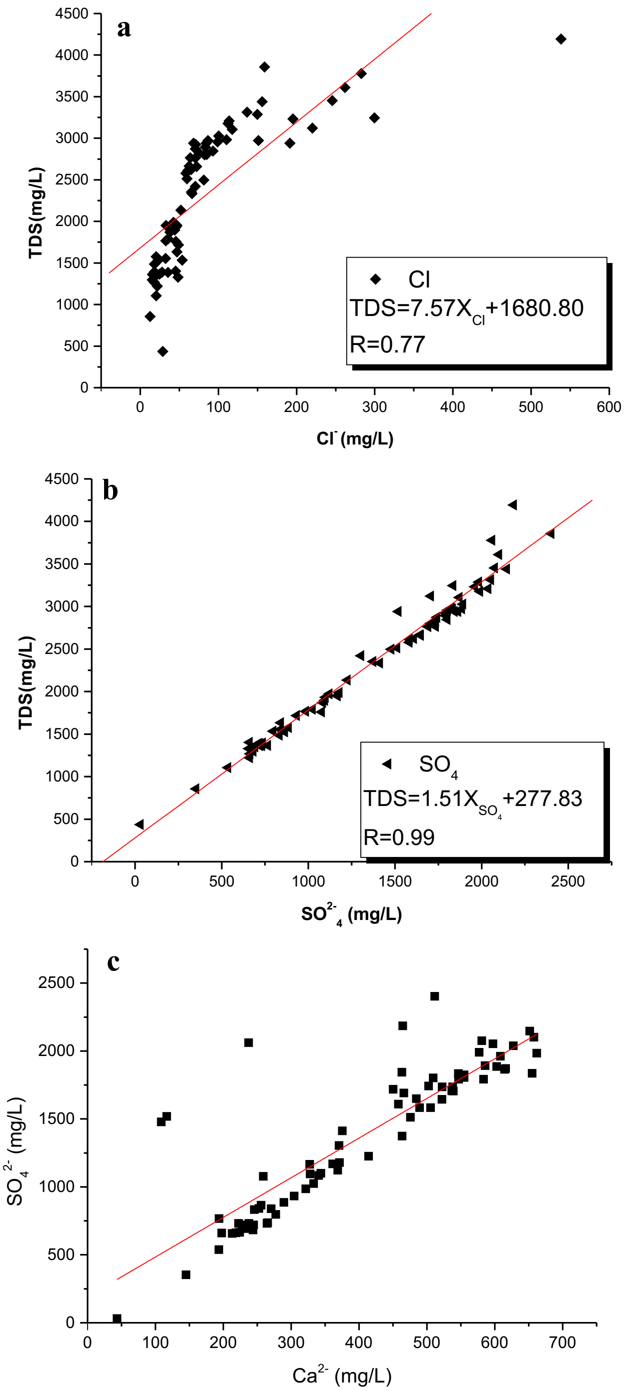
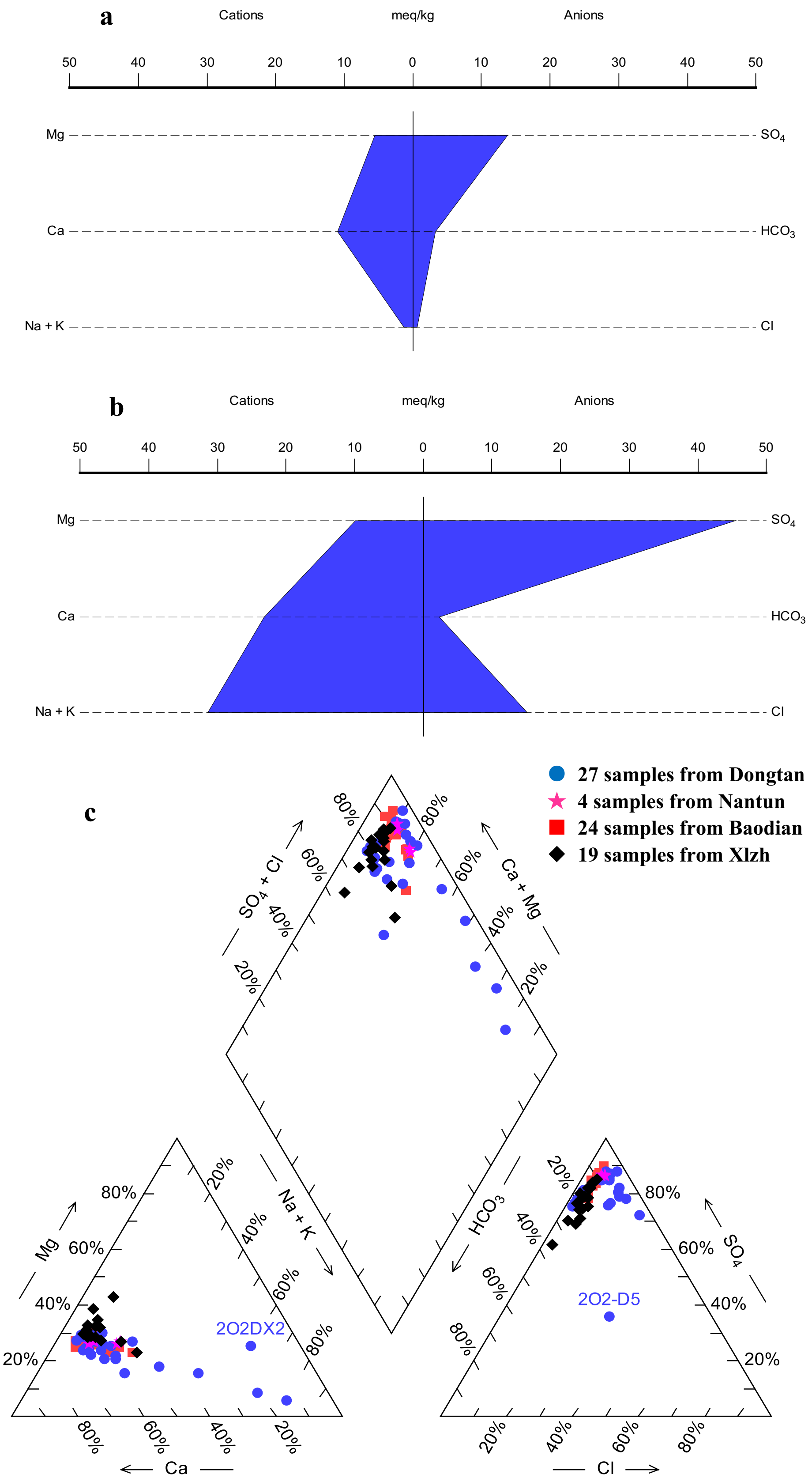


Fig. 8 TDS and major ion relationships: **a** TDS versus Cl^{-}; **b**TDS versus SO_4^{2-}; and **c** SO_4^{2-} versus Ca^{2+}

Fig. 9 Major ion character of the Ordovician groundwaters: **a** Stiff diagram for low TDS groundwaters (TDS < 2 g/L); **b** Stiff diagram for high TDS groundwaters (TDS > 4 g/L); **c** Piper diagram for all water samples



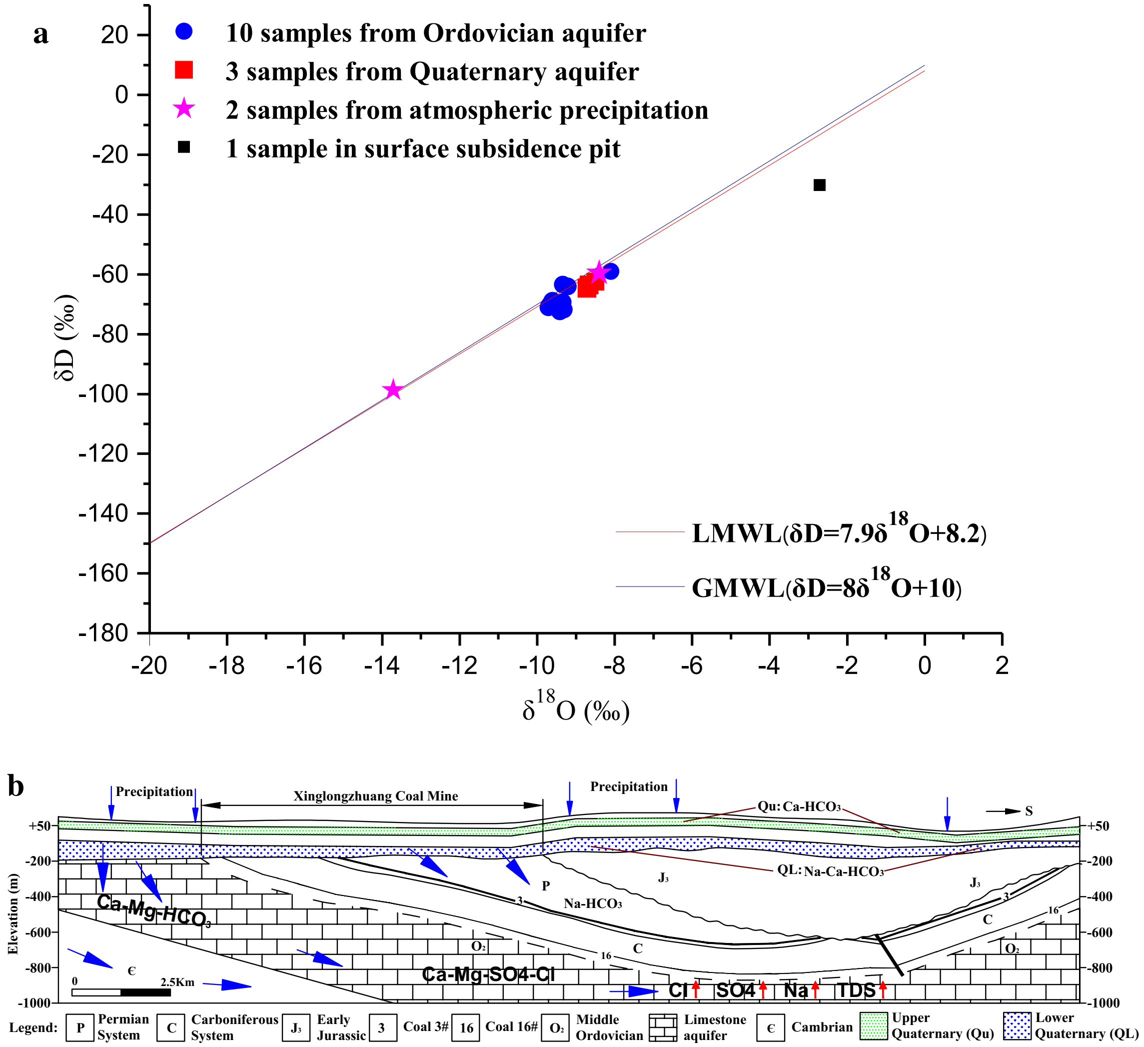


Fig. 10 **a** Relationship between δD and $\delta^{18}O$. **b** Hydrogeological conceptual model

MAT253 isotope ratio mass spectrometer at the China University of Mining and Technology (Li et al. 2013).

To investigate the hydraulic characteristics of the aquifer, various tests were performed to determine both traditional aquifer parameters (transmissivity T and storativity S) and the "unit water inflow" (q), a commonly accepted index in China that indicates a well's ability to supply water. "q" represents the flow rate (yield) that can be obtained from a "standard" diameter well (91 mm) for a 10 m drawdown. Generally, in China, according to the SACMSC (2009), four zones of high unit water inflow can be identified: slight yielding ability ($q < 0.1$ L s^{-1} m^{-1}), moderate yielding ability (0.1 L s^{-1} $m^{-1} < q < 1.0$ L s^{-1} m^{-1}), strong yielding ability (1.0 L s^{-1} $m^{-1} < q < 5.0$ L s^{-1} m^{-1}), and extra strong yielding ability ($q > 5.0$ L s^{-1} m^{-1}).

Aquifer parameters T and S were obtained from an in situ drainage test conducted in the Xinglongzhuang coal mine that involved the simultaneous pumping of two underground dewatering boreholes FO_2-S2 and FO_2-6. The wells are separated by a distance of 1236.85 m. The general setting of these dewatering boreholes is illustrated in Fig. 6. FO_2-S2 was drilled to a depth of 171 m from an in-mine "ground" elevation of − 249.97 masl. FO_2-6 was drilled 67 m deep from an in-mine "ground" elevation of − 346.98 masl. FO_2-S2 had an initial water pressure of 2.8 MPa as indicated by a pressure gage at the wellhead, and yielded 263 m^3/h during the test. FO_2-6 showed an initial water pressure of 3.8 MPa and yielded 126 m^3/h.

Pumping started at 19:00 on October 4, 2016, and finished at 19:00 on October 9, 2016 for a total duration of 120 h. During the pumping phase, heads were monitored in 20 ground-surface wells and 13 underground wells. Following pumping, monitoring was continued during the recovery phase for a further 120 h. Analysis was performed using curve-matching and linear graphical methods for the test's drawdown and recovery, as described by China Geological

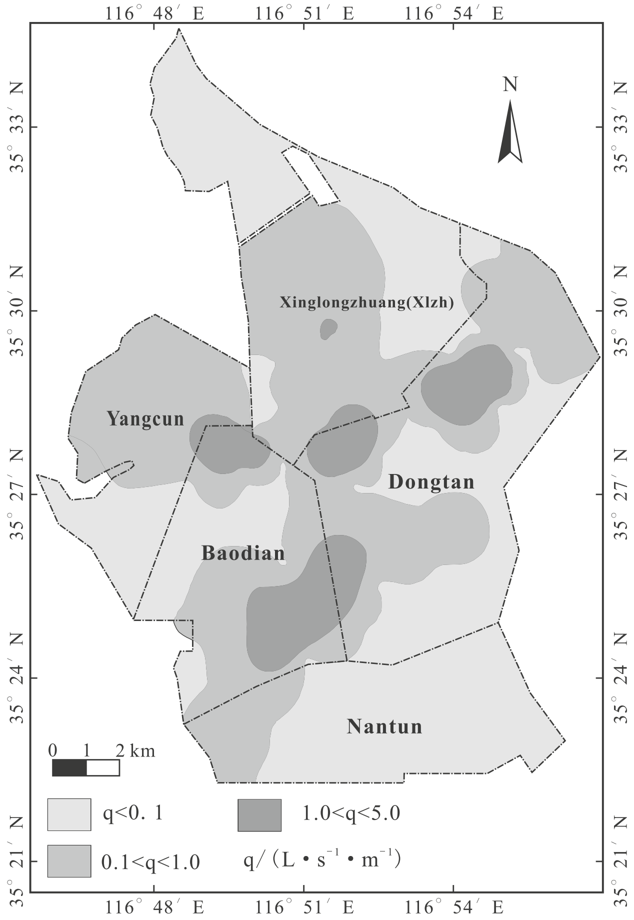


Fig. 11 Distribution of "unit water inflow" (*q*) for the Ordovician limestone aquifer

Survey (2012). Subsequently, the test response was used to help calibrate a study area flow model developed using Waterloo Hydrogeologic's Visual MODFLOW, a commercial version of the MODLOW finite-difference code developed by the U.S. Geological Survey (USGS) (McDonald and Harbaugh 1988), which is widely used in the word (Scibek and Allen 2006; Fan et al. 2007; Laattoe et al. 2014; Romero and Silver 2006).

Results and analysis

Hydrogeochemistry

The groundwater hydrochemistry varies regionally, but also changes significantly as a function of depth. Figure 7 shows TDS (Total Dissolved Solids) in the Ordovician limestone immediately beneath the 5 Yanzhou coalfield mines operated by the Yankuang Group. TDS ranges from 436 to 4193 mg/L corresponding to chloride concentrations ranging from 12.7 to 538 mg/L (Fig. 8a). Salinities increase towards the southeast and prevail at depth. TDS correlates most strongly with SO_4^{2-} (Fig. 8a) which ranges from 153 to 2402 mg/L. In turn, SO_4^{2-} concentration generally correlates strongly with Ca^{2+} (Fig. 8c), although there are some exceptions where high sulphate waters show anomalously low calcium and likely reflect ion exchange and/or precipitation of gypsum. It is pertinent to point out that groundwaters underlying the Xinglongzhuang mine are the freshest in terms of water quality (< 2 g/L). This is why, the Xinglongzhuang coal mine region was identified as an ideal candidate for exploring opportunities for coordinated exploitation of both coal and deep groundwater resources.

Stiff and Piper diagrams are shown in Fig. 9. The Stiff diagrams shown in Fig. 9a and b correspond to the average concentrations observed in groundwaters with TDS values < 2 g/L and > 4 g/L, respectively. While lower TDS groundwaters are clearly Ca-SO_4 in character, higher TDS groundwaters adopt a Na-SO_4 character that largely reflects the role of ion exchange with Na increasing at the expense of Ca. The Piper diagram (Fig. 9c) reinforces this interpretation. The majority of samples plot in zone A of the cation field and zone F of the anion field indicating the prevalence of a Ca-SO_4-type water. However, some samples show a slight dominance of sodium over calcium and can be characterized as Na-SO_4 in type.

The stable isotope compositions of selected samples of Ordovician groundwater are plotted in Fig. 10a where they are compared with the Global Meteoric Water Line, the Local Meteoric Water Line, and the stable isotope characteristics of samples from other sources (Zhao et al. 2009; Al-Charideh and Kattaa 2016). The data are consistent with a local, relatively recent, origin for the Ordovician groundwaters, in all likelihood the aquifer receiving natural recharge via precipitation in the west of the study area where the limestone is exposed at surface. And as mentioned above and the local groundwater chemistry of other aquifers, the hydro-geochemical conceptual model could be obtained in Fig. 10b.

Hydraulic testing results

Values of "unit water inflow" (*q*) for the Ordovician limestone aquifer were obtained at 39 surface and underground sites and contoured using Kriging. Knowledge of these zones is important as they can reveal target areas for siting dewatering wells. The resultant map is shown in Fig. 11. Three of these zones lie either within or along the boundary of the Dongtan coal mine; one small zone lies near the center of the Xinglongzhuang coal mine.

The Ordovician limestone's transmissivity (*T*), storativity (*S*), and hydraulic diffusivity (*D*) (the ratio of transmissivity to storativity) were determined from the analysis of the in situ drainage test. Values were obtained individually for each of the observation wells using curve-matching. Examples of the analytical approach are shown in Fig. 12 and relatively satisfactory results in four directions are summarized in Table 1. They reveal significant regional variability in transmissivity with highest values obtained for observation wells toward the north and west, and much lower values obtained for wells toward the center of the basin in the south and east. The upper boundary of the model is impermeable and the low boundary is treated as impermeable, because the upper 100 m of the Ordovician aquifer is a relatively independent aquifer and is the most dangerous water-inrush source.

Aquifer modeling

To better understand the feasibility for coordinated exploitation of both coal and deep groundwater resources and carry out hydrophobic pressure drop and extracted flow simulation, an aquifer modeling must be established based on the practice dewatering test. Application of the finite-difference model based on MODFLOW began with the establishment of appropriate boundary conditions (Kang et al. 2011). These are shown in Fig. 13. The modeled area does not include the Nantun coal mine comparing with Fig. 1a. Because the observed wells in Nantun are not available during drainage test. Boundaries to the north and east are established which are the basis of major faults. To the north, the Ziyang fault has a throw of > 360 m and is demonstrably impermeable based on the different Ordovician water levels in wells on both sides of the fault according to the hydrogeological data of Xingcun Coal Mine on the other side of the fault. The boundary to the east is also impermeable due to the Yishan fault which has a throw of around 2 km. The boundary along the western edge of the model is a recharge boundary with known flux according to the results of water equilibrium analysis of local geological information, while the Huangfu fault in the south is treated as a head-dependent flux boundary. It is reasonably assumed that flows into the model remain relatively constant during dewatering operations and that the water removed by the dewatering intercepts natural flow in the

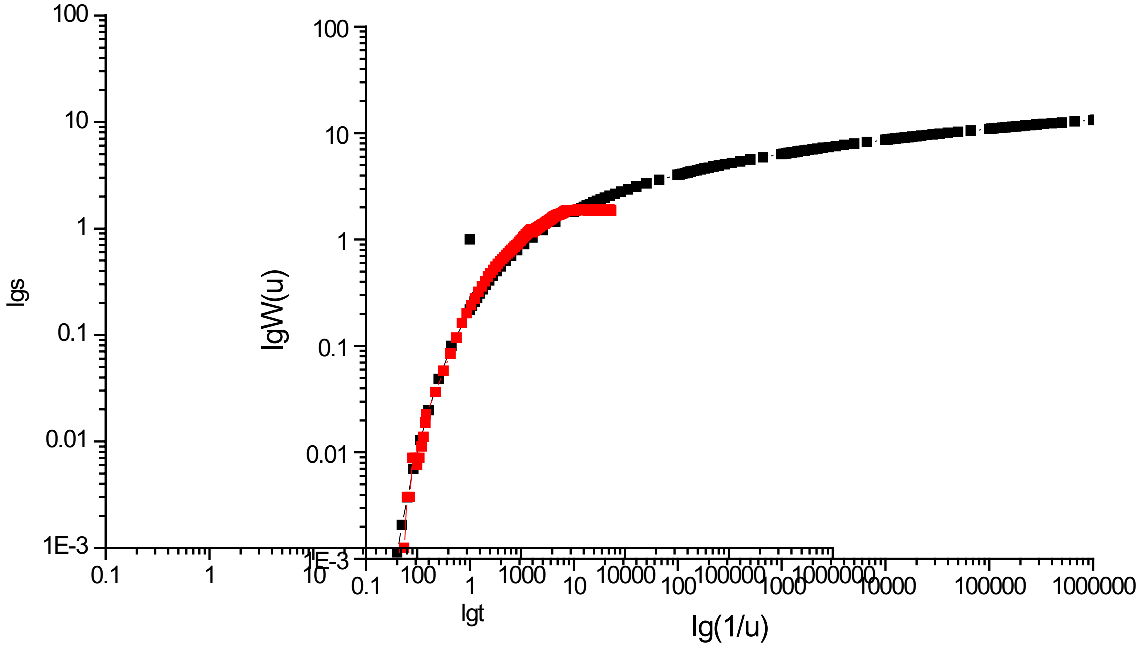


Fig. 12 Examples showing the three methods used for determining aquifer parameters: curve-matching

Table 1 A summary of hydrogeological parameters obtained by curve-matching

Drainage zone	Direction	*S*	*T* (m^2/d)	*D* (m^2/d)
Boreholes FO$_2$-S2 and FO$_2$-6	East of drainage zone	1.13E−04	934	8,228,621
	West of drainage zone	1.48E−04	5857	39,569,555
	North of drainage zone	9.92E−05	4358	43,907,443
	South of drainage zone	1.98 E−04	329	69,008

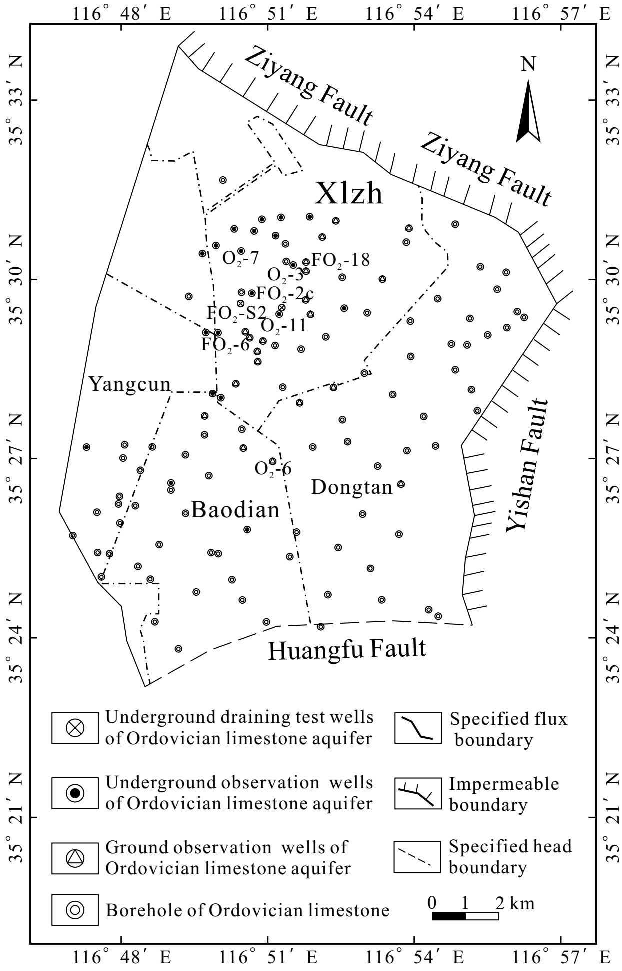


Fig. 13 Hydrogeological conceptual model of Ordovician limestone aquifer in Yanzhou Coal

system, thereby reducing the discharge of water across the boundary to the south.

The model was developed in two dimensions (i.e., as a single-layer) using grid dimensions of 200 m × 200 m and 100 m × 100 m (Fig. 14a). In total, the model included 93 rows, 112 columns, and 10,416 cells, of which 6,650 were active. The model was divided into 18 zones for the assignment of aquifer parameters (Fig. 14b).

As a starting condition, the aquifer was assumed to be in steady state. This is reasonable given that the aquifer has not been developed previously in the model area. Initial heads were assigned according to heads observed during the period 0:00 to 19:00 October 4, 2016, i.e., the period immediately prior to the commencement of the in situ drainage test. In this way, data from the subsequent drainage test could be used to calibrate the model. The model was run repeatedly for both the drawdown and recovery phases of the test, each time adjusting the aquifer parameters to improve the correlation between observed heads and modelled heads.

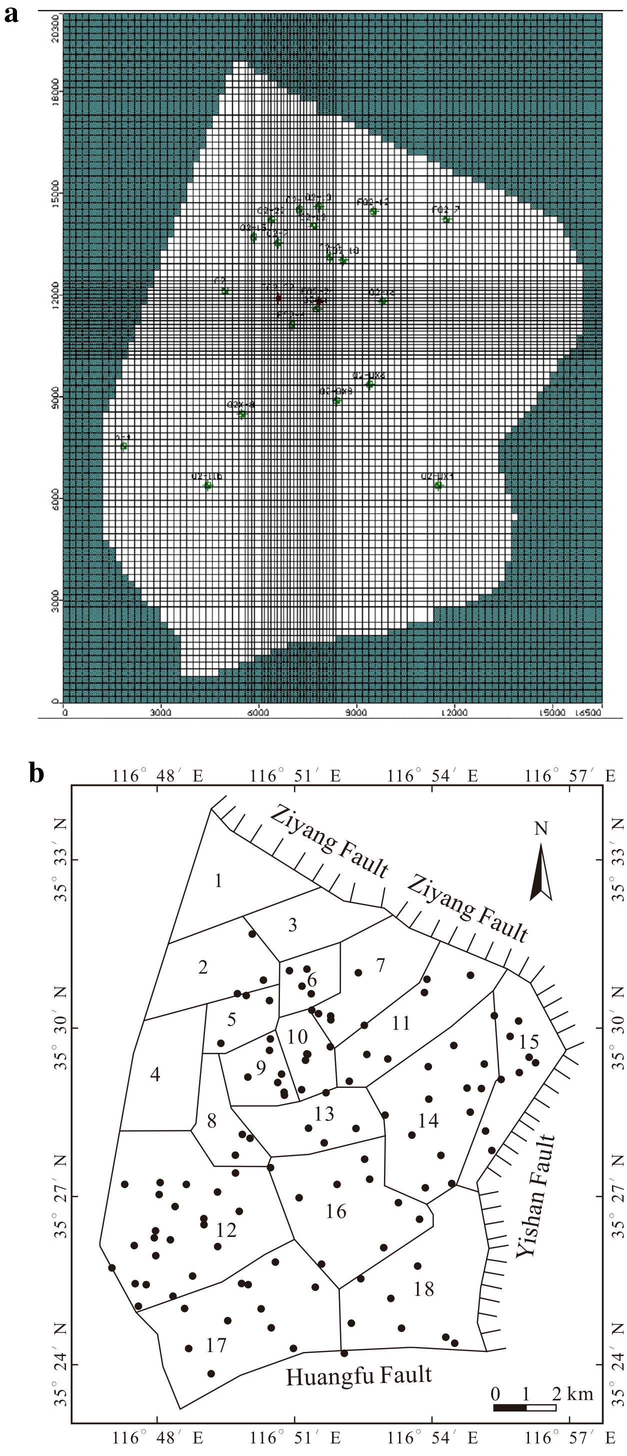


Fig. 14 **a** Model grid and **b** parameter zonation of numerical simulation model

Figure 15 compares observed and modelled heads over the duration of the test for selected observation wells following completion of the calibration process. The observation wells in Fig. 15 are around the drainage wells, and the distance between the observation holes and the drainage holes

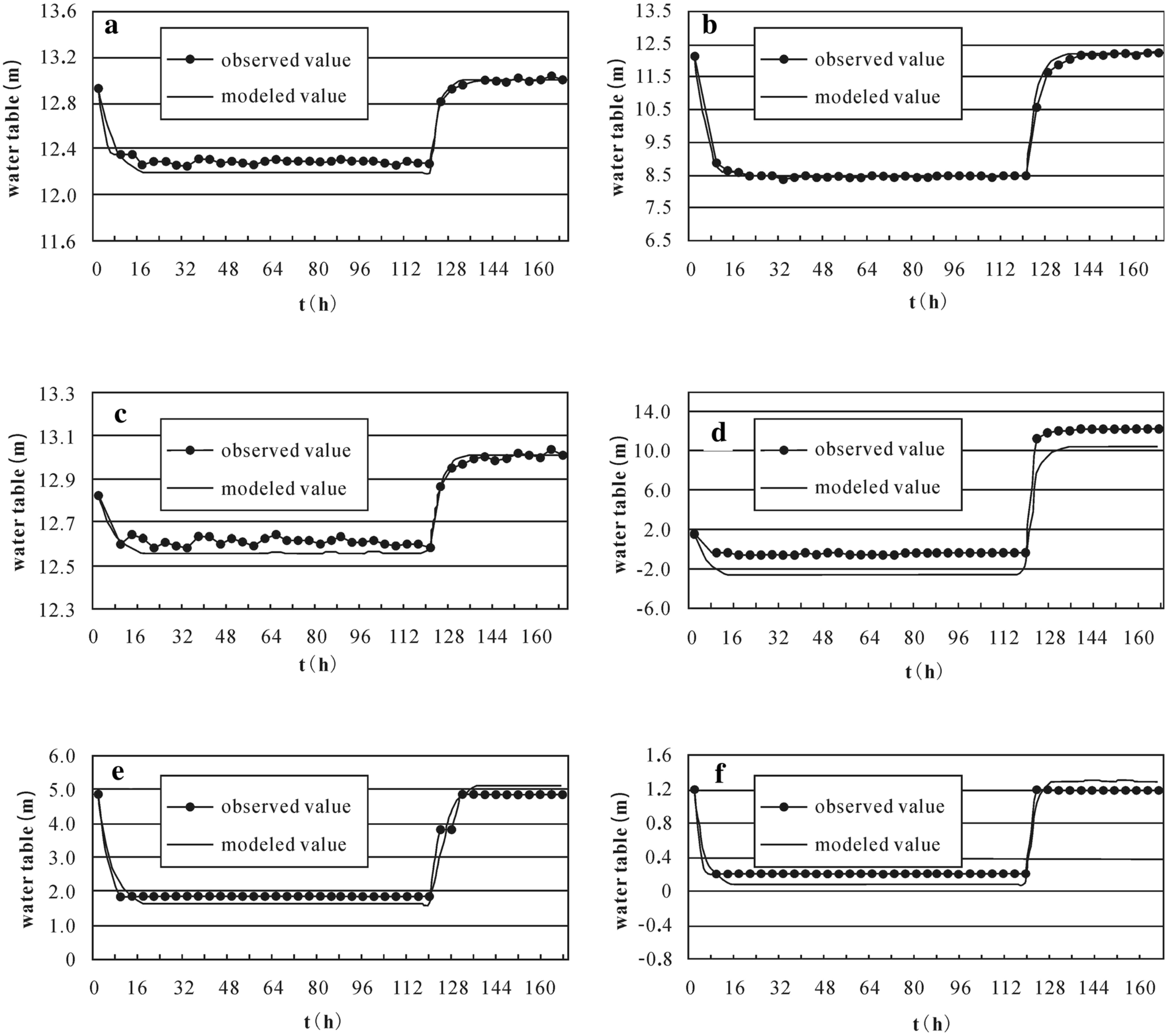


Fig. 15 Groundwater level fitting curve of some observation wells of Ordovician limestone aquifer: **a** Borehole O2-3; **b** Borehole O2-6; **c** Borehole O2-7; **d** Borehole O2-11; **e** Borehole FO2-6; **f** Borehole FO2-18

is also taken into account. Figure 15d shows a little more deviation between observed value and modeled value, which likely means that the hydraulic parameters in the zone of O_2-11 are larger than the actual value, but this is the adjusting result of the model. Good agreement is demonstrated. Figure 16a shows observed and modeled heads at the end of the drawdown phase of the drainage test. Again, there is good agreement. Due to the drainage test which is expensive and the pressure from environment, Xinglongzhuang coal mine did not decide to carry out in situ drainage test using other underground wells for this model in 2016. However, another in situ drainage test at Xinglongzhuang coal mine was performed in 2017, but the observed wells just distribute in Xinglongzhuang coal mine. Therefore, a part of model established on in situ drainage test of 2016 could be generally calibrated by the in situ drainage test of 2017. Due to some limitations of field conditions, three underground wells, FO_2-8, FO_2-12, and FO_2-18, and just 16 observed wells in Xinglongzhuang coal mine were selected for the in situ drainage test of 2017. The total inflows of the three wells are about 175.5 m^3/h. The time period for fitting data for model identification is from 23:00 on March 24, 2017 to 23:00 on March 28, 2017. The model zones and hydraulic parameters of the calibrating model are in accord with the part of Xinglongzhuang of the model established on in situ drainage test of 2016. Observed and calculated water levels meet the convergence conditions (Fig. 16b). The relative error of the fitting point is relatively small, and the fit

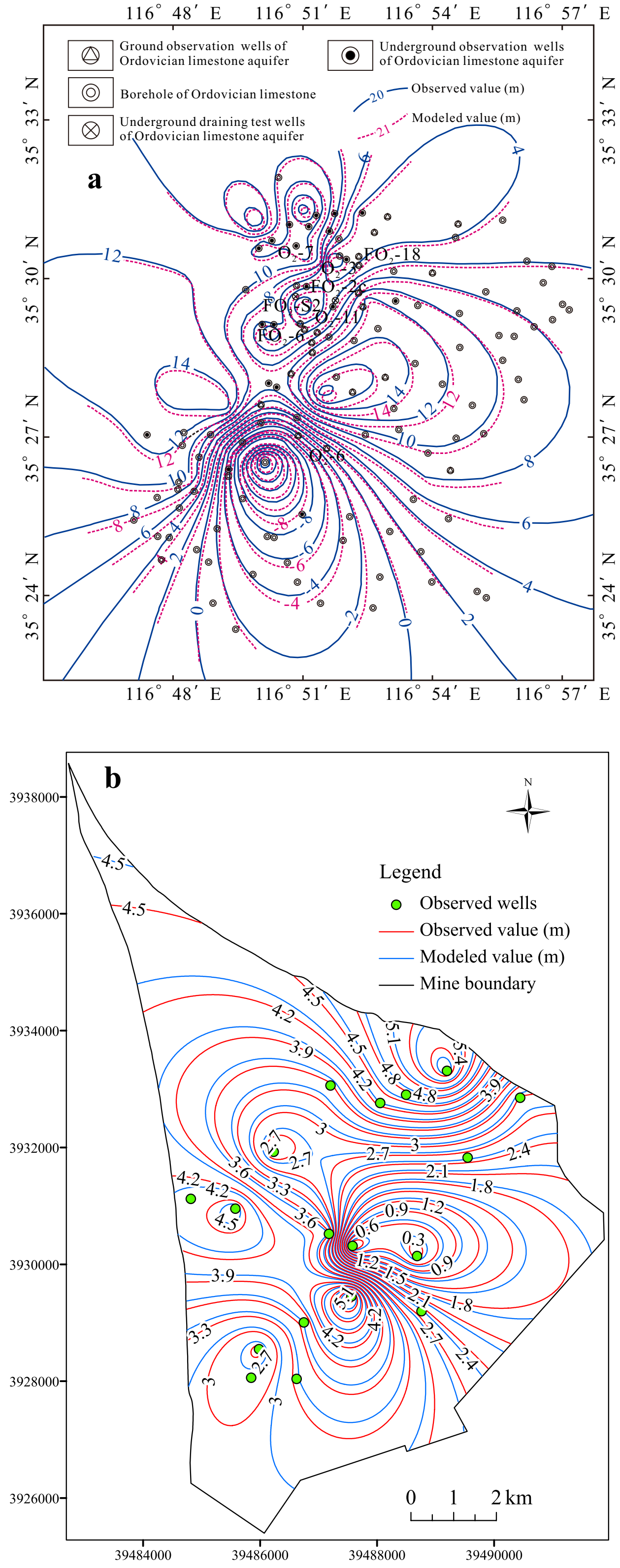


Fig. 16 Groundwater levels contour map between observation and simulation at the end of dewatering test: **a** model identification; **b** model verification

Table 2 Aquifer parameters for each parameter zone following model calibration

zone	T (m^2/d)	S	D (m^2/d)
1	2409.6	4.99E−05	4.83E+07
2	2351.0	4.26E−05	5.52E+07
3	3014.4	6.02E−05	5.01E+07
4	1699.2	1.03E−05	1.64E+08
5	1036.8	6.19E−05	1.67E+07
6	1838.9	4.56E−05	4.03E+07
7	2390.4	9.14E−05	2.62E+07
8	2958.2	1.29E−05	2.29E+08
9	3672.0	9.99E−05	3.67E+07
10	1305.6	8.82E−05	1.48E+07
11	1445.8	8.75E−05	1.65E+07
12	921.6	5.60E−06	1.64E+08
13	1185.6	1.10E−04	1.08E+07
14	173.8	2.19E−05	7.94E+06
15	242.4	7.02E−05	3.45E+06
16	207.4	6.50E−05	3.19E+06
17	61.4	1.16E−05	5.31E+06
18	2246.4	9.02E−05	2.49E+07

is excellent. Table 2 shows the aquifer properties used for each of the parameter zones following model calibration. As expected, the values are broadly consistent values determined by analysis of the test pumping data for individual monitoring wells.

The groundwater flow balance for the aquifer at the end of the pumping phase is shown in Table 3. Water pumped from the dewatering wells (drainage flow − 9336 m^3/d) intercepts around 13% of the natural flow through the system.

Model implementation

The model was subsequently used to explore alternative pumping scenarios, most notably related to the deep coal-mining activities, and the possibility that the water pumped during development of the mine could be put to beneficial use.

In terms of mining coal seams Nos. 16 and 17, the issue of paramount importance is the risk of water inrush and the safety of the miners working at the coalface. In China, a water-inrush forecasting method has been developed and is published in the Regulation for Coal Mine Water Prevention and Control, China (SACMSC 2009). It involves the calculation of a water-inrush coefficient T_s (MPa/m) according to the equation $T_s = P/M$, where P is the water pressure, in MPa, acting on the aquitard between the coalface and the aquifer (the water-inrush source) and M is the thickness of the aquitard in metres (m) (Li et al. 2017). Based on the

Table 3 Groundwater flow balance with the drainage flow of 9454.32 m^3/d

Inflow		Outflow		Drainage flow		Balanced flow (error in the simulated water balance)	
(m^3/h)	(m^3/d)	(m^3/h)	(m^3/d)	(m^3/h)	(m^3/d)	(m^3/h)	(m^3/d)
3019.00	72,456.00	− 2625.15	− 63,003.60	− 393.93	− 9454.32	− 0.08	− 1.92

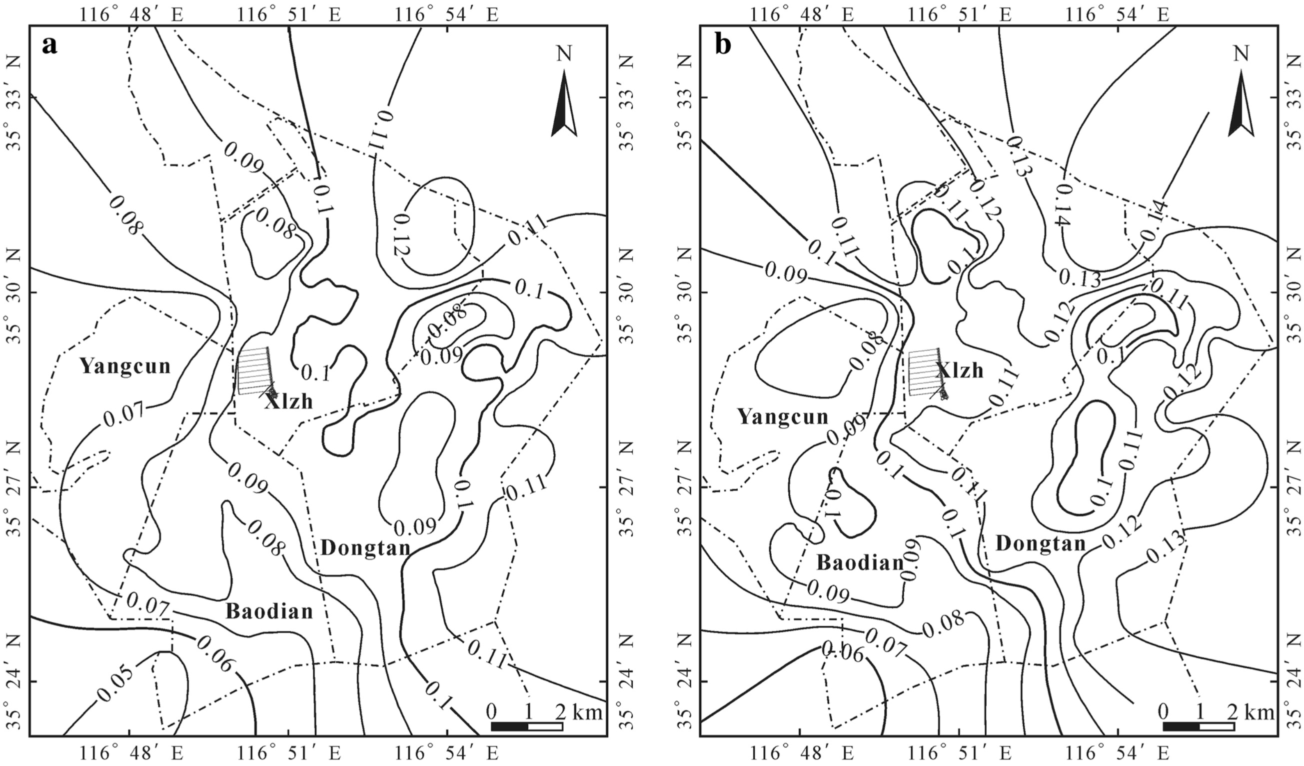


Fig. 17 Water-inrush coefficient of Ordovician with natural water table: **a** Coal No. 16; **b** Coal No. 17

Table 4 Water balance for drainage flow of 64,800 m^3/d (Scheme #1)

Inflow (m^3/d)	Outflow (m^3/d)	Drainage flow (m^3/d)
72,456	− 7688	− 64,800

analysis of large datasets, SACMSC (2009) suggests that water inrush tends not to occur if T_s is less than 0.06 MPa/m in areas with geological structures (e.g., permeable faults) or less than 0.10 MPa/m in areas devoid of significant geological structures. In Fig. 17, contours of the water-inrush coefficient are shown for coal seams Nos. 16 and 17 under natural pre-pumping conditions. It shows that while mining of seam No. 16 could be safe without pumping, mining of seam No. 17 would only be safe if T_s were to be reduced by alleviating aquifer pressures through dewatering.

To explore the feasibility of mining seam No. 17, various pumping options were investigated using the groundwater flow model, two of which are briefly described here. In the first scenario (Scheme #1), 9 wells are pumped at a rate of 7200 m^3/d per borehole for a period of 9 years. While this would generate a drawdown of 180 m in the aquifer underlying the mine zone and guarantee mine safety by a wide margin it would, as shown by the water balance in Table 4, intercept close to 90% of the natural flow in the aquifer and likely affect very seriously the aquifer's downstream hydrogeological function. It was found that the best option (Scheme #2) is to use six pumping wells discharging at a rate of 7200 m^3/d per borehole for a period of just 6 years. This generates of a maximum drawdown of only 110 m but as shown by the water-inrush coefficients on Fig. 18, provide a sufficient safety margin for coal-mining operations to proceed.

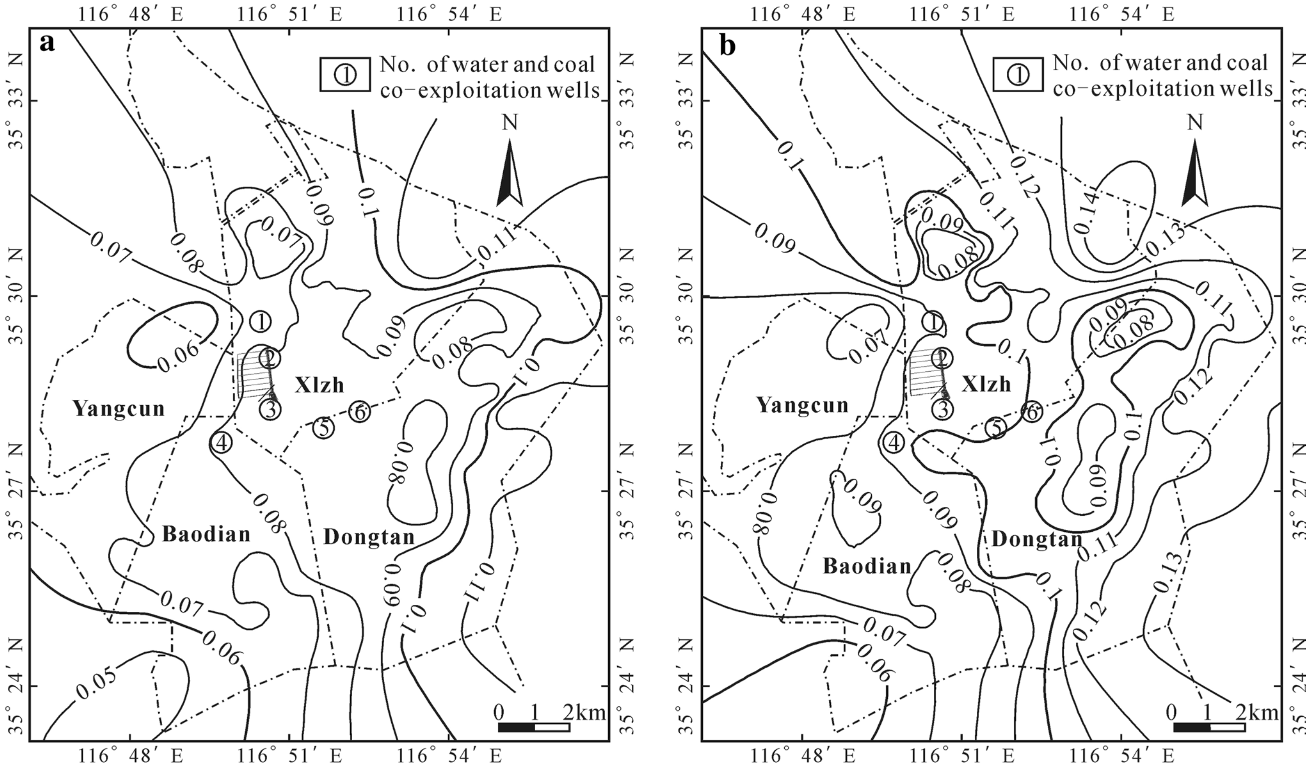


Fig. 18 Water-inrush coefficient of Ordovician with drained water table: **a** Coal No. 16; **b** Coal No. 17

Table 5 Water balance for drainage flow of 43,200 m^3/d (Scheme #2)

Inflow (m^3/d)	Outflow (m^3/d)	Drainage flow (m^3/d)
72,456	− 29,274	− 43,200

Moreover, as shown by the water balance in Table 5, dewatering intercepts only 60% of the natural aquifer flow.

Proposed use of the pumped water

In terms of proposed use of the groundwater for beneficial purposes, water quality is an important consideration. Table 6 shows the major ion chemistry for samples of groundwater from the Ordovician aquifer in the immediate vicinity of the Xinglongzhuang coal mine. In terms of China's drinking water quality standards (Ministry of Health of the PRC and Standardization Administration of the PRC 2006), China's industrial water standard (the reuse of urban recycling water—water quality standard for industrial uses of PRC 2005), and WHO standards (WHO 2011), the water quality is generally good with values of TDS consistently less than 2000 mg/l. However, water hardness and sulphate concentrations disqualify its use for drinking water and some industrial purposes. Fortuitously, the required dewatering pumping rate (43,200 m^3/d) is consistent with anticipated demand in the area for cooling water (30,000–40,000 m^3/d) in the coal chemical industry. Although some treatment may be required, notably to reduce sulphate concentrations, the water is needed and will be readily welcomed by the local industry.

Concluding discussion

The extractive industries are a frequent source of annoyance to the water-supply industry. Deep coal mining is especially problematic. Pollution of valuable water resources is only part of the problem. Dewatering to maintain safe conditions in deep mines diverts large volumes of aquifer water to waste, and can radically alter groundwater flow directions and impact both water levels and water quality in municipal well fields and individual wells. Moreover, dewatering is normally carried out with little understanding of the regional hydrogeology or knowledge of the aquifer parameters, the goal being simply to pump water in sufficiently large quantities to lower heads in the extractive zone to pre-determined target levels. Scant regard is also given to water quality. The only interest in water chemistry is to ensure that the water pumped will meet any regulatory standards with respect to disposal.

Table 6 Major ion analyses for the Ordovician aquifer underlying the XIzh coal mine

Sample	pH	K^+ (mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	HCO_3^- (mg/L)	TDS (mg/L)
O_2-1	7.7	7.9	36.92	333	94.36	35.88	1024.79	230.15	1790
O_2-2	7.8	11.7	52.11	369	100.45	44.47	1121.52	240.11	1971
O_2-3	7.4	11.7	58.42	304	86.64	49.05	932.94	243.84	1717
O_2-4	7.7	8.4	37.84	277	79.11	53.62	796.97	241.35	1534
O_2-6	7.8	9.9	44.80	371	108.08	42.62	1178.61	212.38	1987
O_2-7	7.5	5.7	26.12	219	66.63	21.87	661.56	198.93	1220
O_2-8	7.7	12.5	50.00	259	139.23	45.67	1076.92	159.95	1759
O_2-9	7.3	9.0	41.62	341	97.95	38.04	1083.95	241.95	1870
O_2-10	8.6	6.8	23.67	246	102.39	18.07	832.84	235.23	1486
O_2-11	7.7	12.3	50.00	327	121.78	47.07	1165.56	208.34	1951
O_2-15	7.3	5.4	21.54	194	54.78	20.45	537.11	256.38	1104
O_2-16	7.8	11.9	62.96	271	74.66	32.33	839.12	232.54	1555

In Shandong Province, eastern China, the Yankuang Group has adopted a scientific approach to its development of the Yanzhou coalfield by exploring the feasibility of utilizing water pumped from its dewatering wells to meet the water-supply needs of local industry. To facilitate this goal, additional work was required in terms of pumping test analyses to determine aquifer properties, the development of a groundwater flow model to investigate dewatering strategies and a study of major ion hydrochemistry to understand regional groundwater quality and options for water use. However, this investment will pay dividends to the company in terms of the goodwill generated through its responsible intentions. In terms of the hydrogeological study conducted, some refinement of the model may be required before the work can be reliably implemented, especially with regard to the boundary conditions. However, the coordinated exploitation approach demonstrated in this unusual case study does provide an excellent example of wise environmental stewardship that other extractive industries would do well to consider.

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Author contributions WQ performed implementation and organized the field test, and wrote the manuscript. KH revised the manuscript. WL participated in drafting the manuscript. XZ and SZ collected and analyzed the data. YN drew and revised the figures.

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