




Groundwater environmental risk assessment of abandoned coal mine in each phase of the mine life cycle: a case study of Hongshan coal mine, North China

Haibo Feng¹ · Jianwei Zhou¹  · Bo Chai¹ · Aiguo Zhou¹ · Jianzhong Li^{1,2} · Henghua Zhu^{1,3} · Hongnian Chen^{1,4} · Danhui Su¹

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Abstract

Human activities during each phase of coal mine life cycle greatly affect groundwater environment. The groundwater environment destruction is not just only the destruction of underground structure but also the social problems caused by available groundwater resources reduction, as well as the environmental problems affecting ecosystem and human health. Moreover, the groundwater environmental risk of coal mining is complex, dynamic, and long-term. Therefore, a framework and quantitative method for groundwater environmental risk analysis at different phases of the mine life cycle was presented, which is composed of the groundwater system destruction risk (GSDR) and social-economic-ecological vulnerability (SEEV) assessment. The framework was applied in Hongshan abandoned coal mine, North China. Based on the aquifer structure destruction, groundwater flow field evolution, contamination, and social-economic influence analysis, 12 main controlling factors for the GSDR and 7 factors for the SEEV were determined and quantified separately. The results showed that the groundwater contamination of the Hongshan mine mainly occurred after closure, caused by the cross-strata pollution of mine water, which significantly reduced the groundwater available resources, which greatly affected local social-economy sustainable development and residents' health. The Hongshan mine closure increased groundwater environmental risk, with the GSDR high-risk zone being 12.51 km² larger than that during the mining phase and the SEEV was calculated at a high level. This framework promotes systematic integration of the groundwater environmental risk assessment in mine life cycle.

Keywords Coal mine · Groundwater environmental risk assessment · Mine life cycle · Cross-strata pollution · Vulnerability analysis

Highlights

1. Groundwater aquifer structure destruction, flow field evolution, and contamination were studied.
2. A new framework for groundwater environmental risk assessment of coal mine life cycle was proposed.
3. Combining social, economic, and ecological vulnerability analysis in risk assessment.
4. Mine closure might increase groundwater environmental risk.

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✉ Jianwei Zhou
jw.zhou@cug.edu.cn

¹ School of Environmental Studies, China University of Geosciences, Wuhan 430074, Hubei, China

² Department of National Spatial Ecological Rehabilitation, Ministry of Natural Resources of the People's Republic of China, Beijing 100812, China

³ Shandong Institute of Geological Survey, Jinan 250013, Shandong, China

⁴ Shandong Lunan Institute of Geological Engineering Survey, Yanzhou 272100, Shandong, China

Introduction

Up to now, coal still plays a leading role in the energy structure of many countries of the world, including Europe, the USA, South Africa, China, and Australia (Wu et al. 2020). According to the global reserve-production ratio in 2018, the world's coal can be produced for 132 years at existing production levels (Corporation BP 2019), which means it is not a sunset industry (Gadonneix and Nadeau 2013). Since the Industrial Revolution of the eighteenth and nineteenth centuries, coal mining has produced serious environmental problems with backward mining technologies in the past 250 years (Dulias 2016). Thus, the amount of abandoned coal mines is increasing rapidly as the governments successively put forward the policy that closing illegal and unreasonable coal mines since the twenty-first century (Ryan 2017). For example, the number of closed or abandoned mines is expected to reach 12,000 by 2020 in China alone (He et al. 2019). And the groundwater environmental problems caused by coal mining and closure have become a key factor restricting the local social, economic, and ecological sustainable development for a long time. Therefore, researching the groundwater environmental risk of coal mines in their life cycle is very important, which has received substantial attention from government and society.

The concept of “life cycle” can be generally understood as the whole process from “cradle-to-grave” (Zhu 2004; Ma et al. 2010). Life cycle assessment is an evaluation of a product, process, or activity from generation to extinction and the effect after extinction (Finnveden et al. 2009). Life cycle theory has been widely used in the fields of various products and

industries; environmental impact assessment in the human economic society and the mining industry are no exception (Ditsele and Awuah 2012). Mine life cycle includes the whole processes of prospecting, constructing, mining, and closing and the period following the closure of mines (Tang et al. 2013). At the same time, the geological environment in mine areas also has a corresponding evolution cycle (Dai et al. 2017) (Fig. 1). The factor analysis before mining is the background values of the groundwater environment, including ore geology, hydrogeology, ecological environment, groundwater exploitation activities, and industrial structure. Mining activities are the critical factors of mine hazards in the mining stage, causing aquifer structure destruction, surface subsidence, water bursting, and fault activation (Zeng et al. 2016; Sun et al. 2018; Liu et al. 2019), forming groundwater descend funnels (Sun et al. 2015; Wei et al. 2016; Liu et al. 2017), and producing acid mine drainage (Yacoub et al. 2014; Wright et al. 2015; Galhardi and Bonotto 2016) (Fig. 1). When stop pumping after closure, the mine water level would rise rapidly and could enter deep or shallow aquifers, resulting in contamination (Fig. 1). For these groundwater environmental problems which always last for years or decades, it is very important to face the economic restructuring and water utilization structure conversion with the mine closure. Thus, the risk assessment should be emphasized for clean groundwater resource reduction and negative impact of social economy (Fourie and Bren 2006; Zhang et al. 2009; Fan 2011; Voulvoulis et al. 2013; Klerk et al. 2016; Pandey et al. 2016).

In recent years, there are numerous papers on the groundwater environment of coal mine, mainly about the problems of mine water-irruption (Wu et al. 2014, 2015, 2016), descend

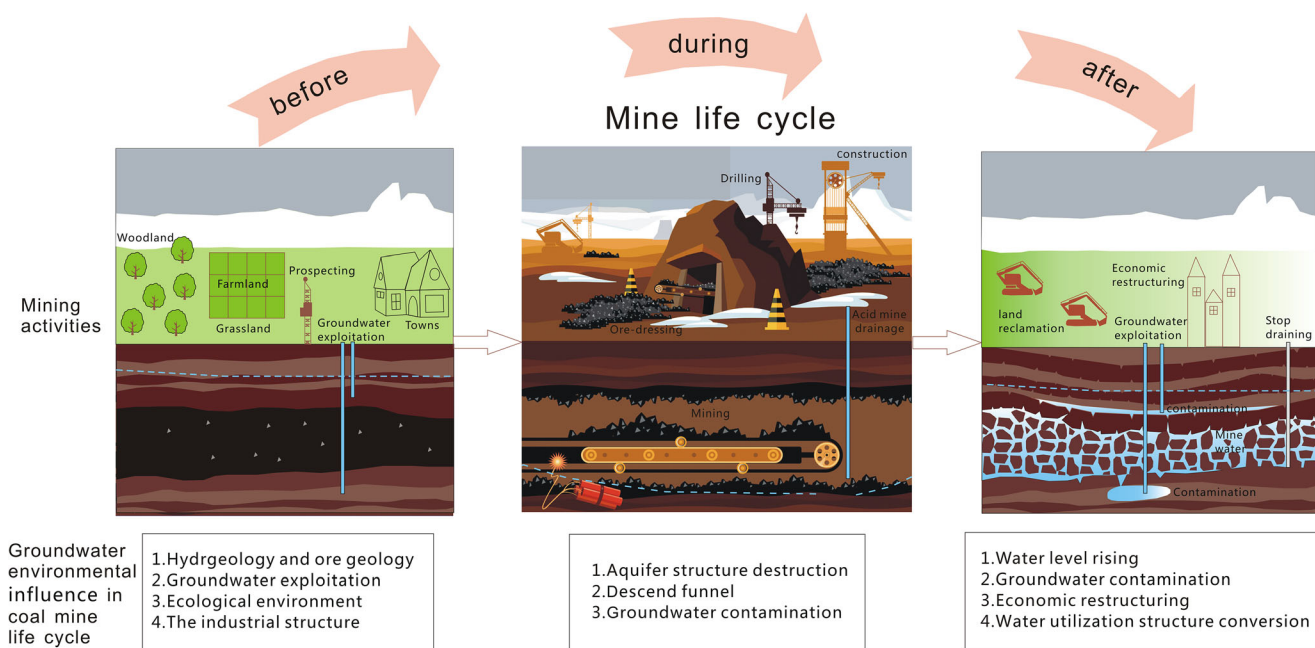


Fig. 1 Coal mine life cycle and the groundwater environmental influence

funnels, land subsidence (Sun et al. 2015), and contamination (Zhou et al. 2018). Although most factors of groundwater environmental destruction were covered, these studies are specific to a problem and unilaterally aimed at only one stage of the mine life cycle. In the 11th Mine Closure Conference in 2016, there were 58 articles that specialized in abandoned mines; only one was about long-term groundwater management (Garrick et al. 2016). And most of the researches focused on soil restoration and vegetation reconstruction. Thus, research on abandoned coal mine groundwater environment is very limited, and there are few studies about the systematic analysis in the coal mine life cycle (Cardoso 2015; Dai et al. 2017). Moreover, the present researches about mine environmental risk assessments are mainly concentrated on geological hazard and heavy metal pollution risk (Düzgün 2005; Shi et al. 2013; Li and Ji 2017; Lei et al. 2015; Teng et al. 2019). It is a pity that the risk assessment methods applied to abrupt geological hazards and health risks of harmful pollutants cannot be comprehensively applied to the risk of groundwater environmental destruction (Fedeski and Gwilliam 2007; Gao et al. 2020). The destruction of groundwater environment is a comprehensive problem of the geological structure destruction, the clean groundwater resource reduction, and substantial danger to public health or the ecosystem (Fourie and Bren 2006). Therefore, it is very important to perform a proper technical framework for groundwater environmental risk assessment in mine life cycle.

As a typical case of the abandoned coal mine, Hongshan mine lies in Zibo City, Shandong Province, which was built in 1904 and closed in 1994. At the life cycle, there were many groundwater environmental problems with the Ordovician limestone aquifer contamination being the most serious. This aquifer is extensive as an important source of potable and producing water by local residents. According to statistics, the local residents have a low water per capita ratio, approximately 379 m³/person, which is only 16.7% of the country's average (2300 m³/person), far below the world's lowest standard (1000 m³/person) (Fan 2007; Song 2007; Wang et al. 2014). Thus, the aquifer contamination further declined the water supply capacity and greatly affected the life and production of Zibo's citizen (Zhou et al. 2018). In this study, hydrogeological monitoring combined with the data of coal mine life in different historical periods was adopted to reveal the groundwater system evolution laws and social-economic influence. Moreover, a quantitative method was proposed for groundwater environmental risk assessment at each phase of mine life cycle. The results not only offer an active exploration of groundwater resource management of Hongshan coal mine but also offer new feasible thought and reference for the risk assessment of similar coal mine.

Materials and methods

Background of the study area

The area of Hongshan coal mine is located in Zichuan District, Zibo City, with an area of 67.9 km² (Fig. 2). This region has the typical subtropical humid monsoon climate, with annual precipitation of 659.4 mm and annual evaporation of 1345.7 mm. The Jinchuan River flows through the study area, running south to north, and the Nuanshui River traverses the north-western region (Fig. 2).

The geological conditions of Hongshan coal mine are complicated, with well-developed faults and folds. The hydraulic conductivity of Mansihe and Beifocun Faults is very small, which forms the northern and southeastern boundary of the mine field. But the hydraulic conductivity of Panlongshan and Quanzizhuang Faults is high, which forms the western and southwestern boundary of the mine field. Fenghuangshan Fault, Wazi Fault, and Qianyu Fault are all water-conducting faults (Fig. 2). The major stratigraphic from old to new are Cambrian system (Є), Ordovician (O₂), Carboniferous (C), Permian (P), Triassic (T), Jurassic (J), and Quaternary (Q) (Fig. 3). The coal-bearing strata of the mine field are Taiyuan Formation of the upper Carboniferous (C3t) and Shanxi Formation of the Lower Permian (P1sh), with a total of 10 layers, including coal #2, #2–1, #3, #5, #7, #8, #9, #10–1, #10–2, and #10–3, respectively. The coal seams #7, #9, and #10 is the main minable layer of the Taiyuan Formation (C3t). The thickness of #10 is 2.19–6.0 m, which is the thickest minable layer of the Hongshan mine.

The Zichuan groundwater system can be divided into three major aquifer systems. The first is mainly loosely pored aquifer of Quaternary (Q) with sand and sandy gravel, which is supplied by the atmospheric precipitation recharge. The thickness varies from 10 to 15 m, with a layer of argillaceous gravel at the bottom. The second is Permo-Carboniferous fissure aquifer with mainly sand shale; water yield property is weak. The third is Ordovician limestone (O₂) aquifer, mainly recharged by atmospheric precipitation and river infiltration. The yielding amount increasing from southeast to northwest, with the highest zone located in Luocun Town (Fig. 2). The aquitard between fissure aquifer and the karst aquifer is the Benxi Formation, with thickness varying from 12.65 to 38.76 m (Fig. 3). Naturally, there is no direct hydraulic affiliation between the two aquifers. The aquifer of Ordovician limestone water is extensively utilized as a good source of potable water, and it produces water to industry and living residents of Zibo City. Therefore, the Ordovician limestone water is at high risk of destruction affected by coal mining activities, and thus, risk assessment is needed.

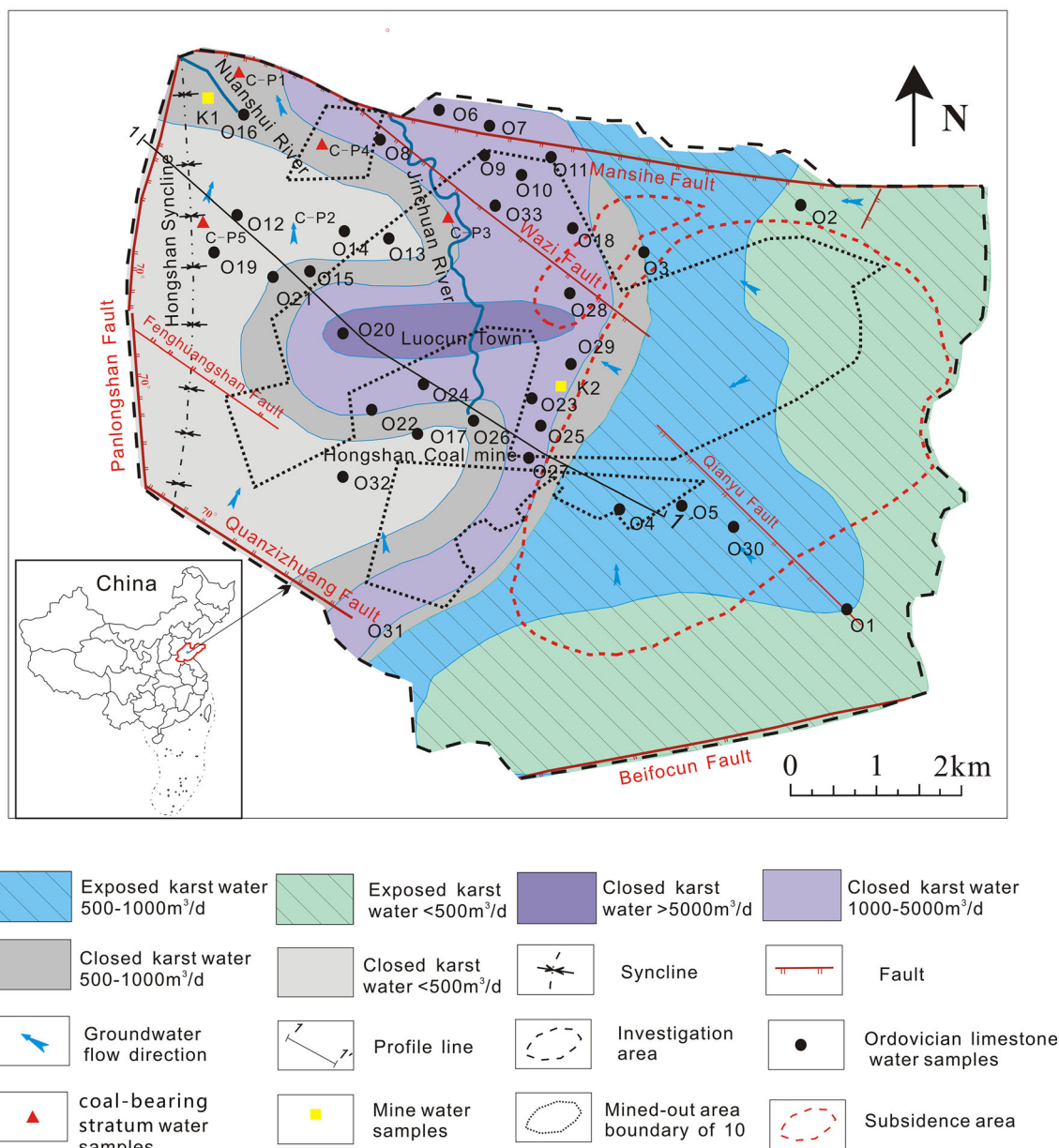


Fig. 2 Ordovician limestone aquifer hydrogeologic map and sampling sites of Hongshan mining area

Data collection

In this study, the data for groundwater environmental risk assessment were taken from investigation reports, mining practice, and other researches on the Hongshan coal mine (Song 2007; Wang 2012; Wu 2013; Sun 2016; Zhou et al. 2018). The water level and quality data of different historical periods in the mining area were provided by Shandong Geological Environment Monitoring Station and Shandong Institute of Geological Survey, and the field investigation and sampling analysis were adopted from 2013 to 2015 (Table 1).

Sample collection and analysis

Forty dynamic groundwater monitoring wells were observed in the Hongshan coal mine area from September 2013 to September 2015, and water samples were collected, including 33 Ordovician limestone waters, 5 Permo-Carboniferous fissure waters, and 2 mine waters (Fig. 2). The water sample collection and analysis methods provided by the Groundwater Environmental Monitoring Technical Regulations (MEPPRC 2004) were followed in detail. All samples were collected after purging the wells for at least 15 min while monitoring field parameters. The data of pH,

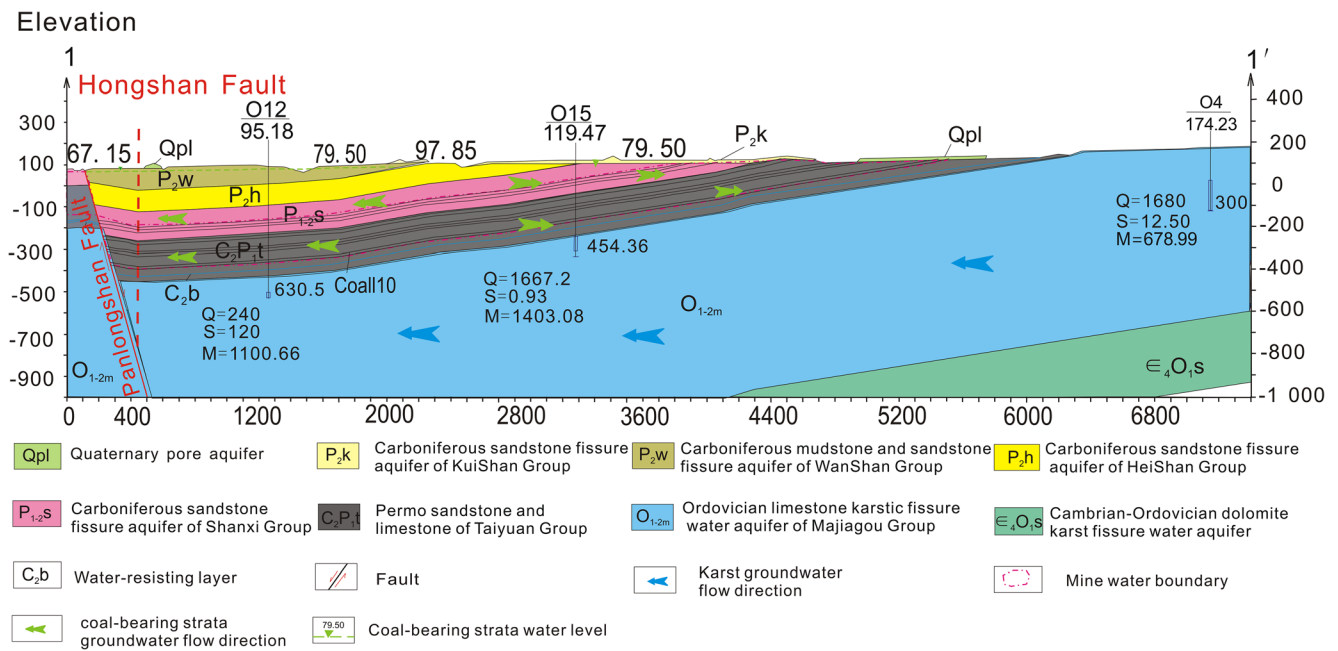


Fig. 3 Hydrogeologic profile of Hongshan mining area

temperature, specific conductance, redox potential, and dissolved oxygen were measured using a portable multi-parameter water quality meter (HQ30d, Sailiwei Corp, Jiangsu, China). Samples were collected into pre-cleaned sterilized 5-L polyethylene bottles through a 0.45- μm syringe filter immediately. All samples were sealed and transported in coolers to the laboratory within 24 h, then placed in a 0–4 °C environment for preservation. In laboratory, Cl^- and SO_4^{2-} were determined using ion chromatography (Metrohm 761/813, Switzerland). The total hardness (TH)

was measured using the EDTA titration method, and salinity was detected by the gravimetric method.

Results and discussion

Groundwater system evolution in coal mine life cycle

Aquifer structure destruction

There were four types of aquifer structure destruction caused by mining activities in the Hongshan coal mine: (1) coal seam roof aquifer destruction, (2) floor aquifer destruction, (3) fault activation, and (4) well destruction (Fig. 4).

During the shallow coal seam mining, the unloading crack zone affected upper Quaternary loose pored aquifer, which made infiltrate and increased the mine water inflow (Fig. 4). The surface subsidence occurred in the eastern part of Luocun Town, with an area of 17.85 km^2 (Fig. 2), owing to the roof aquifer destruction affecting the ground surface directly.

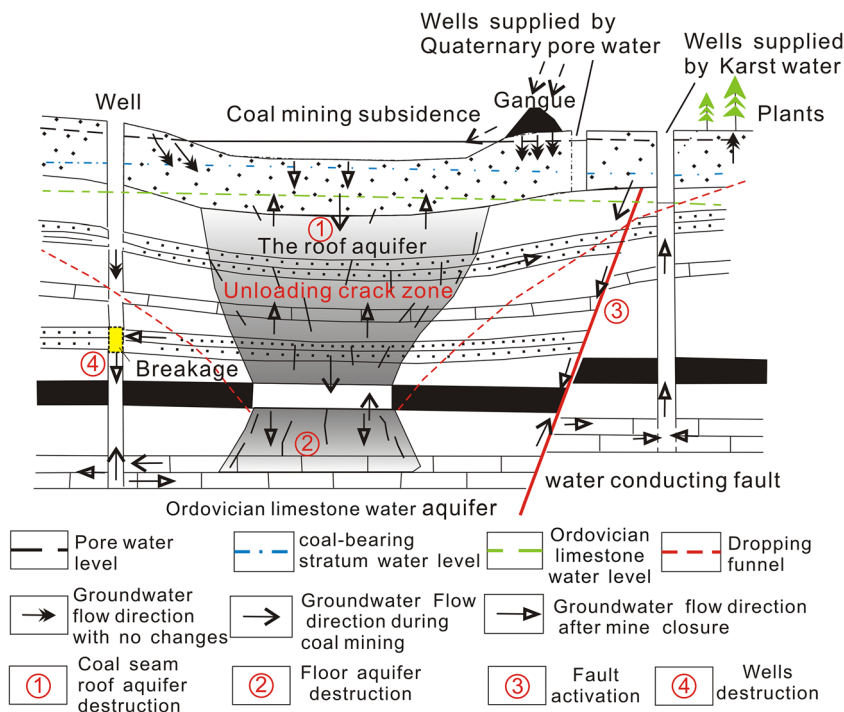
When the deeply buried coal seam was excavated, the floor aquifer encountered a greater hazard of water-inrush from the underlying Ordovician aquifer (Fig. 4). According to the practice of the Hongshan coal mining, the coal seam floor destruction depth generally reaches 10–20 m, and the maximum could reach 41 m (Wu 2013). And 31 floor water-inrush accidents which occurred in the Hongshan coal mining area from 1904 to 1981 were all because of this (Wu 2013).

When coal mining affects the faults or promotes the faults to become active, the faults will shorten the distance between the coal seam and adjacent aquifers (Fig. 4). For example, the

Table 1 Data collection

Type	Data	Data sources
Geology and hydrogeology	Strata, lithology, faults, permeability, water abundance and so on	“Shandong Zibo City Zichuan 1:50000 regional geological survey”
Mining stage	Monitoring data of groundwater quality and level	1. “Shandong Geological Environment Monitoring Station” 2. “Shandong Institute of Geological Survey”
	Mine water bursting hazards	“Hongshan Coal Mine Memorabilia”
After closure	Monitoring data of groundwater quality and level	1. “Shandong Geological Environment Monitoring Station” 2. Sampling and analysis
Socioeconomic status	Socioeconomic structure Water utilization structure	(Song 2007; Wang 2012; Wu 2013; Sun 2016; Zhou et al. 2018)

Fig. 4 Schematic diagram of aquifer structure destruction



water-inrush accident in the Hongshan mining area in 1935 was a typical water-inrush caused by the Wazi Fault (Fig. 2). The average distance between coal seam #10 and the underlying Ordovician aquifer is 67 m in the coal mine area; Wazi Fault shortens this distance with 34-m fault throw, which leads to an instant water-inrush with a water inflow of 442 m³/min.

The stratum deformation and collapse in the Hongshan coal mine area lead to some water supply well destruction. For example, the O20 well was checked by underground closed-circuit television, and it showed that the shaft wall cracked at 63.5–65 m in the coal seam goaf, with large quantities of mine water leaking in. Moreover, the investigation report confirmed that there are eight similar wells in the study area, which are O12, O13, O20, O21, O22, O26, O28, and O33 wells, respectively (Fig. 2).

The coal strata water level rose rapidly after mine closure. Thus, mining fissures, faults, and wells with poor water sealing effects all become channels leading to cross-strata pollution (Fig. 4).

Groundwater flow field evolution

The groundwater flow field before and after mine closure were compared (Fig. 5). The Ordovician limestone water flowed from southeast to northwest in the natural state before closure in 1992, mainly controlled by precipitation and lateral seepage. At that time, the water level of Ordovician limestone was between 0 and 20 m (Fig. 5a). Although the mine water level was –4~–30.9 m owing to the drainage, about 40 m was lower than that of Ordovician limestone water. So the supply

direction between the two aquifers is from bottom to up. In 2003, the mine water level rose rapidly to 54.2~65.5 m; the Ordovician limestone aquifer flow field became complicated, with the groundwater level abnormal near wells O13 and O20 (Fig. 5b). Furthermore, the mine water level continuously rose to 76.0~97.8 m in September 2014, 10~53 m higher than that of Ordovician limestone water level, as the wells O12, O13, O20, O21, O21, O26, O28, and O33 (Fig. 5c). The great difference of water head and the existence of the water channel mentioned above made the cross-strata pollution possible. And the recent studies in the Hongshan coal mine using multi-isotopes (³⁴S, ¹⁸O, ²H) to track groundwater contamination also demonstrated that the cross-strata pollution was a local phenomenon (Zhou et al. 2018).

Groundwater contamination

The Ordovician limestone groundwater is an important source of water supply providing good water quality in Zibo City. Until 1992, the water quality of Zibo City and the Hongshan coal mine was good, and the water chemistry type was mainly HCO₃–Ca·Mg type (Table 2). But after 1994, it was seriously contaminated soon with the mine closure. Taking the well O20 as a case (Table 2), the TH, salinity, Cl[–], and SO₄^{2–} concentrations of all samples presented a sharp rising tendency from 1996 to 2014, with the SO₄^{2–} concentrations in 1996, 2000, 2006, 2013, and 2014 were 4.3, 5.8, 9.9, 12.7 and 22.2 times as high as the background value (Fig. 6). And the hydrochemical type changed from HCO₃–Ca·Mg type to

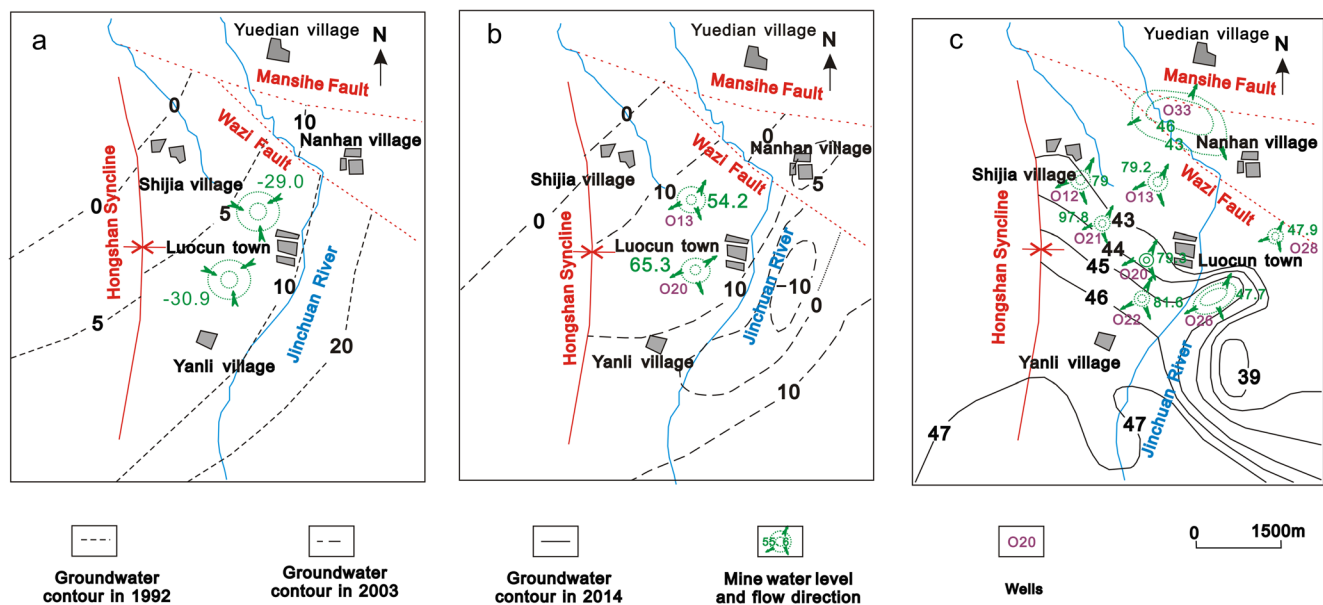


Fig. 5 Groundwater flow field evolution of Hongshan coal mine area

SO₄-Ca-Mg type. It is thus clear that contamination mainly occurred after mine closure.

According to the sampling test and analysis of former research results (Zhou et al. 2018), the groundwater of the Hongshan coal mine area was characterized by high salinity, TH, Cl⁻, and SO₄²⁻ concentrations. Thus, these four indicators were singled out as objective assessment factors. Regional Ordovician limestone water background value was used as evaluation criteria (Table 2). The Nemerow multi-factor index method was applied to evaluate the groundwater contamination, with the formula below:

$$P = \sqrt{\frac{(P_i)_{\max}^2 + (\bar{P}_i)^2}{2}} = \sqrt{\frac{\left(\frac{C_i}{S_i}\right)_{\max}^2 + \left(\frac{1}{n} \sum \frac{C_i}{S_i}\right)^2}{2}} \quad (1)$$

where: P_i is a sub-item pollution index of a pollutant; $(P_i)_{\max}$ is the maximum of P_i in each pollution index; \bar{P}_i is the average of

each pollution index; C_i is the measured concentration of a pollutant; S_i is the evaluation criteria of a pollutant; and n is the number of assessment factors. The assessment results are classified according to the following classification criteria (Table 3).

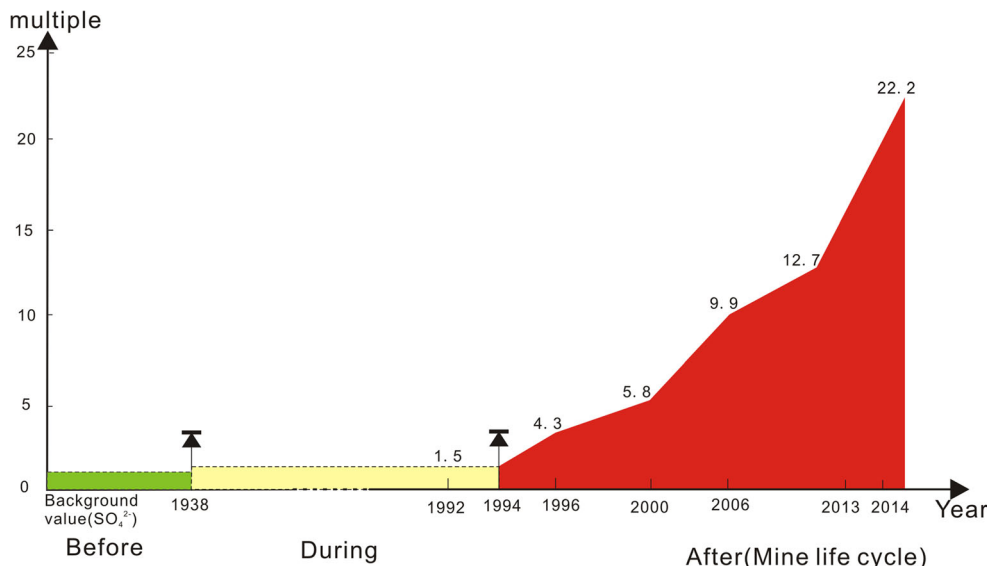
The Surfer13.0 was applied to protract the Ordovician limestone water contamination evaluation zoning map (Table 4). The study area was evaluated as four-level divisions, which were super seriously polluted zone, heavily polluted zone, moderately polluted zone, and lightly polluted zone (Table 3). It indicated that pollution has threatened throughout the study area (Fig. 7), with a super seriously polluted zone distributed in the middle of the study area, about 33.28 km², accounting for 50.23% of the study area. The heavily polluted zone covered 13.76 km², which was mostly band-shaped and surrounding the super seriously polluted zone. The moderately polluted zone was located in the south-east and northeast of Luocun Town with 8.60 km². The lightly

Table 2 Water chemical components of well O20 from the year 1992 to 2014

Year	TH (mg/L)	Salinity (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	Hydro-chemistry type
Background value	248.73	408.60	11.23	58.48	HCO ₃ -Ca·Mg
1992	362.57	587.89	36.15	90.54	HCO ₃ -Ca·Mg
1996	445.34	771.61	29.91	248.55	SO ₄ ·HCO ₃ -Ca·Mg
2000	497.86	863.21	39.40	338.93	SO ₄ ·HCO ₃ -Ca·Mg
2006	771.84	1177.50	42.63	578.94	SO ₄ -Ca·Mg
2013	884.91	1355.35	52.36	741.13	SO ₄ -Ca·Mg
2014	1598.49	2441.35	106.85	1299.90	SO ₄ -Ca·Mg

Background value and the data from 1992 to 2006 were provided by “Shandong Geological Environment Monitoring Station”

Fig. 6 Groundwater SO₄²⁻ concentration evolution of well O20 in the mine life cycle



polluted zone covers an area of 6.62 km², which is more than 1 km away from the Hongshan mining area in the southeast of the study area. Moreover, the groundwater from coal-bearing stratum and mine pits also was evaluated as super seriously polluted type. Thus, it is obvious that the groundwater environment of the coal mine area has been polluted to different degrees owing to the cross-strata pollution. The super seriously polluted zone has exceeded half of the study area, which would bring huge threat to local society, economy, ecology, and residents' health.

Socioeconomic influence in coal mine life cycle

In the coal mine life cycle, the negative impact on social economy is mainly reflected in the restriction of water shortage on local industrial economy, and the social problems caused by groundwater contamination.

In the mining stage, mine drainage is the main factor affecting the groundwater environment (Fig. 8(b–d)). According to statistics of groundwater exploitation in Zichuan District from 1980 to 1994, the water for industry, domestic, irrigation, and mine drainage purposes accounted for 19.1%, 13.7%, 18.8%, and 48.4%, respectively (Fan 2007). The mine drainage reached 0.2069 × 10⁸ m³ per year on average (Wang 2012); it is obvious that the mine drainage

was the main groundwater consumption in those years. Meanwhile, the mining industry was the main body of the social economy at that time, accounted for more than 25% of local economic income (Yu et al. 2003). With insufficient attention to the ecological environment before the 1990s, the social-economic influence was not prominently showed up before the mine closure.

After closure in 1994, the local social and economic structure was changed, with the coal mining industry no longer predominant. But the acid mine drainage (AMD) produced from the Hongshan abandoned coal mine led to serious groundwater contamination. 75.6% of the study area was seriously contaminated (Fig. 7), which significantly reduced groundwater available resources (Fig. 8(a, c)). According to statistics, Zichuan was still dominated by water-consuming industries such as manufacturing, production, and supply of electric power and gas. The three industries' compositions were 3.5, 54.0, and 42.5, among which the secondary industry was the highest (Yu 2017). The total water demand in the Zichuan area was 3.66 × 10⁸ m³/a in 2010, but the available groundwater resources were only 1.81 × 10⁸ m³/a (Yu et al. 2003) (Fig. 8). Until 2017, there were 125 coal enterprises, 18 oil, and 13 gas firms in the study area (Yu 2017). Therefore, the local industrial economy is severely

Table 3 The classified standard of pollution levels and zone division

Pollution levels	I—clean	II—light polluted	III—moderate polluted	IV—heavy polluted	V—super serious polluted
<i>P</i>	< 1	1–2	2–3	3–5	> 5
Area (km ²)	0	6.62	8.60	13.76	33.28

Table 4 Chemical compositions and pollution levels of groundwater in this study

Type	Sample	Depth	TDS (mg/L)	TH (mg/L)	SO ₄ ²⁻ (mg/L)	Cl ⁻ (mg/L)	Multiple pollution index <i>P</i>	Pollution levels	Water type
Ordovician limestone waters	O1	51.5	460.58	289.61	70.86	14.11	1.22	II	HCO ₃ -Ca·Mg
	O2	37.25	623.29	396.76	102.81	14.57	1.65	II	HCO ₃ ·SO ₄ -Ca
	O3	36.5	687.90	420.58	151.90	35.79	2.77	III	HCO ₃ ·SO ₄ -Ca
	O4	40.42	678.99	420.53	135.23	28.63	2.31	III	HCO ₃ ·SO ₄ -Ca·Mg
	O5	39.5	835.72	501.30	176.42	65.14	4.69	IV	HCO ₃ ·SO ₄ -Ca
	O6	41.95	1176.67	623.81	354.42	154.39	10.69	V	SO ₄ ·HCO ₃ ·Cl-Ca·Mg
	O7	51.8	1770.82	994.54	553.41	397.49	26.74	V	SO ₄ ·Cl-Ca·Na
	O8	46.3	460.28	16.72	49.88	40.22	2.72	III	HCO ₃ -Ca·Mg
	O9	42.9	1168.36	676.06	343.62	116.22	8.27	V	SO ₄ ·HCO ₃ -Ca·Na
	O10	41.7	1014.27	559.80	264.11	95.76	6.80	V	SO ₄ ·HCO ₃ -Ca
	O11	37.25	1392.62	593.23	376.47	268.12	18.05	V	SO ₄ ·Cl-Ca·Na
	O12	79.05	1486.78	988.64	735.09	56.34	9.94	V	SO ₄ -Ca·Mg
	O13	78.9	2742.42	1754.53	1241.78	171.41	17.45	V	SO ₄ -Ca·Mg
	O14	42.78	1736.11	121.21	669.19	111.34	9.31	V	SO ₄ -Na
	O15	43.48	996.99	673.86	620.10	56.17	8.35	V	SO ₄ ·HCO ₃ -Ca·Mg
	O16	49.35	795.66	150.77	183.17	50.89	3.68	V	HCO ₃ ·SO ₄ -Na
	O17	45.48	1122.41	771.39	608.52	38.05	5.45	V	SO ₄ ·HCO ₃ -Ca·Mg
	O18	41.75	1507.28	719.05	505.25	224.76	15.46	V	SO ₄ ·HCO ₃ ·Cl-Ca·Na
	O19	43.35	1080.81	661.19	347.33	49.95	5.03	V	SO ₄ ·HCO ₃ -Ca·Mg
	O20	79.3	2441.35	1598.49	1299.9	106.85	17.55	V	SO ₄ -Ca·Mg
	O21	97.8	2881.89	1977.33	1548.94	174.30	21.27	V	SO ₄ -Ca
	O22	81.55	2842.79	2325.49	1443.95	457.75	32.24	V	SO ₄ ·Cl-Ca·Mg
	O23	44.25	1350.30	807.23	433.93	181.01	12.58	V	SO ₄ ·HCO ₃ -Ca·Mg
	O24	44.4	1978.62	1037.07	1076.97	199.33	15.28	V	SO ₄ -Ca
	O25	44.85	1403.13	932.99	568.12	69.90	7.99	V	SO ₄ ·HCO ₃ -Ca·Mg
	O26	47.7	2171.93	1451.79	1019.1	58.11	13.69	V	SO ₄ ·HCO ₃ -Ca·Mg
	O27	41.05	1446.59	851.12	416.92	110.81	8.16	V	SO ₄ ·HCO ₃ -Ca
	O28	47.9	1810.03	1206.69	833.59	59.31	11.29	V	SO ₄ ·HCO ₃ -Ca·Mg
	O29	41.65	1254.91	718.50	223.16	278.17	18.55	V	Cl-HCO ₃ -Ca
	O30	40.65	1421.09	907.92	236.18	240.28	16.19	V	Cl-Ca·Mg
	O31	46.6	747.76	437.24	139.14	19.37	2.16	III	HCO ₃ ·SO ₄ -Ca·Mg
	O32	40.65	304.00	169.85	144.39	29.93	2.21	III	SO ₄ -Mg·Na
	O33	46.58	1229.85	732.46	306.11	45.96	4.58	IV	HCO ₃ ·SO ₄ -Ca·Mg
Permo-Carboniferous fissure waters	C-P1	76.8	1990.31	1283.99	984.41	122.3	13.65	V	SO ₄ -Ca
	C-P2	80.65	2409.51	1586.33	1111.74	167.57	15.73	V	SO ₄ -Ca·Mg
	C-P3	76	2470.72	1302.16	1302.16	143.49	17.75	V	SO ₄ -Ca·Mg
	C-P4	77.22	2593.69	1684.97	1302.16	129.4	17.80	V	SO ₄ -Ca·Mg
	C-P5	86.3	1889.56	1526.17	813.95	285.11	20.02	V	SO ₄ -Ca·Mg
Mine waters	K1	-	2922.15	2036.88	1470.72	183.9	20.43	V	SO ₄ -Ca·Mg
	K2	-	2989.11	2019.12	1472.67	206.54	20.64	V	SO ₄ -Ca·Mg

restricted by the shortage of groundwater resources, facing high risks (Fig. 8(d1)). Moreover, the local residents have a low water per capita ratio of 379 m³/person (Fan 2007; Song 2007), and the groundwater contamination not only aggravates the tension of drinking water but also increases the health risk (Fig. 8(a)).

The framework of groundwater environmental risk assessment

Geological environmental risk is the expected hazard value caused by geological environmental problems, including the estimated losses of population and economy, as well as the

Fig. 7 Groundwater contamination zones of Ordovician limestone water aquifer in Hongshan coal mine

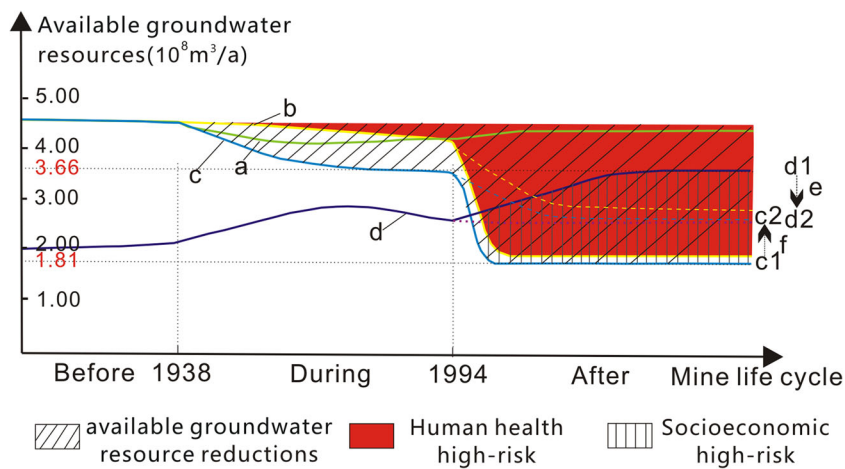
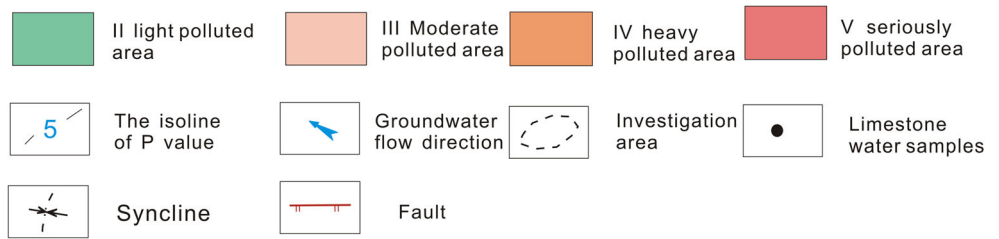
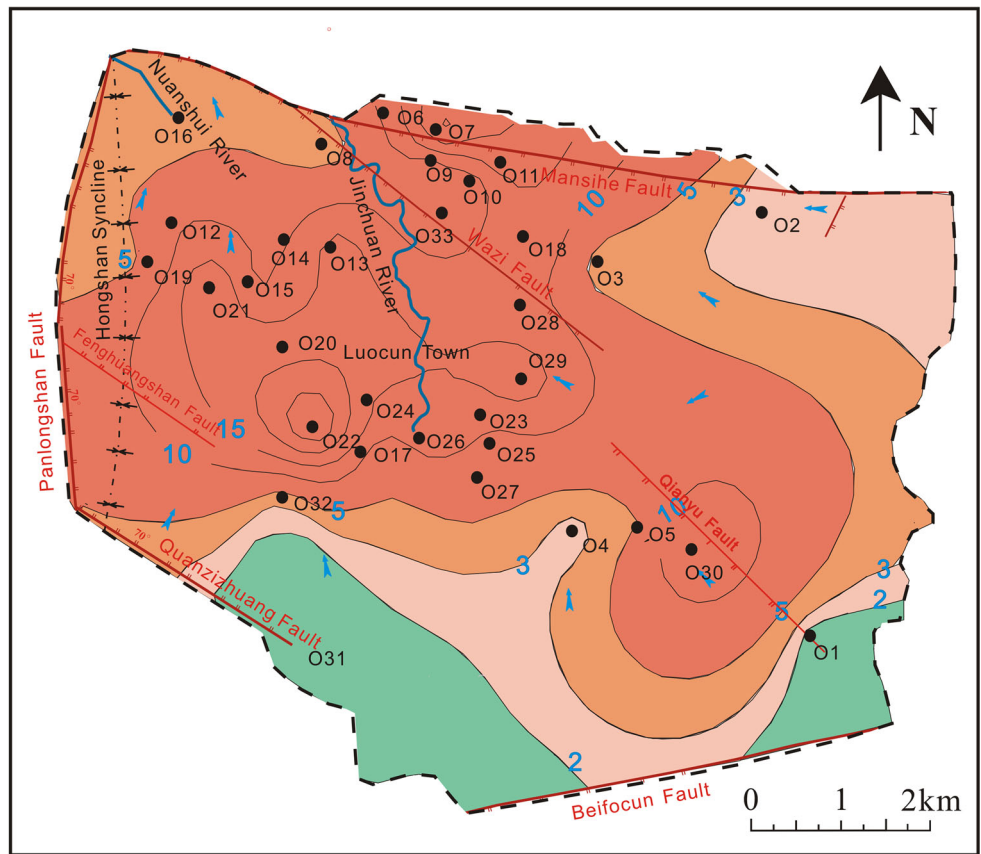


Fig. 8 Groundwater resource evolution and risk composition in mine life cycle of the study area. (a) The variation of groundwater resources due to drainage. (b) The variation of groundwater resources due to contamination. (c) Available groundwater resources (c1 and c2 are corresponding to the treatment of groundwater contamination). (d) Socioeconomic water

consumption (d1 and d2 are corresponding water utilization structure for different economic development modes). (e) The direction of water utilization structure adjustment. (f) The direction of available groundwater resources increasing

impact of society, environment, and ecology. It was first used in abrupt disasters such as landslides (Fell 1994), expressed by casualties and economic losses (Dai et al. 2002). Compared with the abrupt geological hazards, the mine groundwater environmental destruction develops slowly, and the expression forms and content of risk are different. According to the internationally accepted risk assessment framework (Cardona 2011), the technical framework was constructed as shown in Fig. 9. There are 6 steps in the framework.

Step 1: Basic data investigation and collection

The coal mine geological background, exploitation and utilization plan, water utilization structure, ecological environment, socioeconomic conditions, and developing program are the basic data of groundwater environmental risk assessment.

Step 2: Risk identification

According to the analysis of groundwater system destruction forms and its socioeconomic influence in the coal mine life cycle in the “Groundwater system evolution in coal mine life cycle” and “Social-economic influence in coal mine life cycle” sections, the groundwater system destruction risk

(GSDR—the possibility of destruction) and its social, economic, and ecological vulnerability (SEEV) were considered the key elements of the risk assessment. Such gradual geological environmental risk can be predicted by monitoring, statistics, analogy, and simulation (Fig. 9).

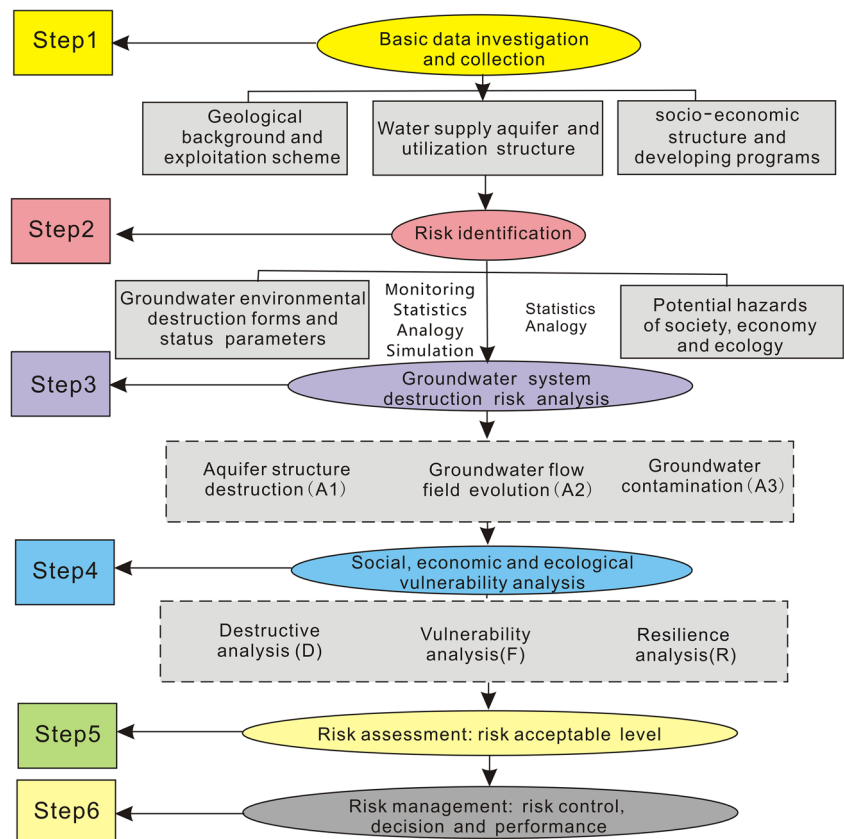
Step 3: Groundwater system destruction risk analysis

The GSDR analysis is mainly the destruction possibility indicator and parameter analysis. The controlling factors are mainly from three aspects of aquifer structure destruction, groundwater flow field evolution, and contamination. The risk analysis is presented in two stages during and after coal mining, respectively.

Step 4: Social, economic, and ecological vulnerability analysis

The SEEV of coal mining is related to their destructiveness, fragility, and resilience. Local socioeconomic structure and ecological environment conditions are the main parameters for vulnerability analysis (Tang et al. 2013). The social and economic destruction is reflected in available groundwater resources reduction and residents’ health problems caused by groundwater contamination (Voulvoulis et al. 2013; Clemens et al. 2020). Ecological destruction is mainly

Fig. 9 Framework of coal mine groundwater environmental risk assessment



focusing on the damage of vegetation supported by groundwater. Social and economic fragility is mainly related to the local industrial structure and water utilization structure; the higher dependency of groundwater leads to higher fragility. Ecological fragility is reflected in the stability of the ecosystem and the dependency of groundwater. The resilience analysis means the recovery ability of the groundwater environment ecologically and socioeconomically.

Step 5: Risk assessment

Risk assessment is the process of determining the acceptable risk level. In fact, because of individual differences in environmental protection consciousness, and regional differences in economy and culture, the environmental acceptable risk level would be affected. Therefore, the risk assessment needs the participation of economists, sociologists, mine owners, government departments, and residents, etc. According to the risk assessment standard of the USA, the UK, Australia, etc., the criteria for individual acceptance, societal acceptance, and ecological acceptance are the core content (Bell et al. 2006). The ALARP (as low as reasonably practicable) standard was widely used in individual risk assessment, with a target reference risk range of 10^{-4} – 10^{-6} (1 chance in 100 million of developing cancer) (Paul et al. 2001). The societal risk acceptance can be carried out through questionnaire. The ecological risk acceptance is mainly related to the ecosystem quality and risk tolerance; the function and role of the ecological environment in the regional economy and society also play a significant role (Ban et al. 2015).

Step 6: Risk management

Risk management focuses on risk control, decision, and performance (Tang et al. 2013). Among them, risk control is an effective measure to reduce risk, mainly including three categories: reducing the GSDR through the protection and control measures in the mining process, reducing the vulnerability through adjusting and optimizing the industrial and ecological structure, and reducing the groundwater environmental risk through education, supervision, etc.

Groundwater environmental risk analysis and assessment in study area

Risk analysis and assessment

The GSDR assessment model was proposed based on the above analysis of groundwater system destruction forms in the Hongshan coal mine area. Aquifer structure destruction, groundwater flow field evolution, and contamination constituted the criteria hierarchy. And 12 main controlling indexes

comprehensively constituted the decision-making hierarchy, including all factors that may lead to groundwater system destruction in the coal mine life cycle, which are shown in Fig. 10.

Firstly, the analytic hierarchy process (AHP) method was used to quantify the relative significance of each major factor in controlling groundwater system destruction and to calculate the weight of these controlling factors to the overall goal (Li et al. 2015). The influence weight calculation was presented in two stages during and after coal mining, respectively. The controlling indexes were evaluated with the expert evaluation method and rated with the 1–9 scale method founded by Saaty (1977), according to the aquifer structure destruction, groundwater flow field evolution, and contamination characteristic analysis before and after coal mine closure in “Groundwater system evolution in coal mine life cycle.” In practice, each of the proposed main factors are put into a table, and experts of various fields were consulted to evaluate and score for each factor according to their roles in the groundwater system destruction before and after coal mine closure phase. The final cumulative scores are compared between the various indexes and form evaluation sets for each index (Wu et al. 2014); then, the judgment matrix of the AHP was built. Through matrix operations, each major controlling index was assigned a weighting factor (Table 5).

The index classification was carried out by referring to industry regulations, expert judgment, statistics, and empirical values (Table 5). The states and parameters of each index were determined based on the hydrogeological conditions and the borehole data analysis of the mining area. Then, as scored by experts, the attribute database of each controlling index was established with the Kriging interpolation method, and the thematic maps of the 12 main indexes were built using GIS spatial function (Dai et al. 2018). The thematic maps of B7, B10, and B11 were different during and after coal mining; the others were the same, as shown in Figs. 11 and 12.

The information storage layers of each controlling factor can be put into a single layer through complex superimposition, and the integrated layer includes all of the information of the related factors (Zhang et al. 1994). The model of GSDR can be expressed as follows:

$$R = \sum_{i=1}^n \alpha_i \times f_{B_i}(x, y) \quad (2)$$

where R is the GSDR composite index; α is the weight of a controlling factor; $f_{B_i}(x, y)$ is the contribution function of the main controlling indexes; x, y are the geographical coordinates; and n is the number of controlling factors.

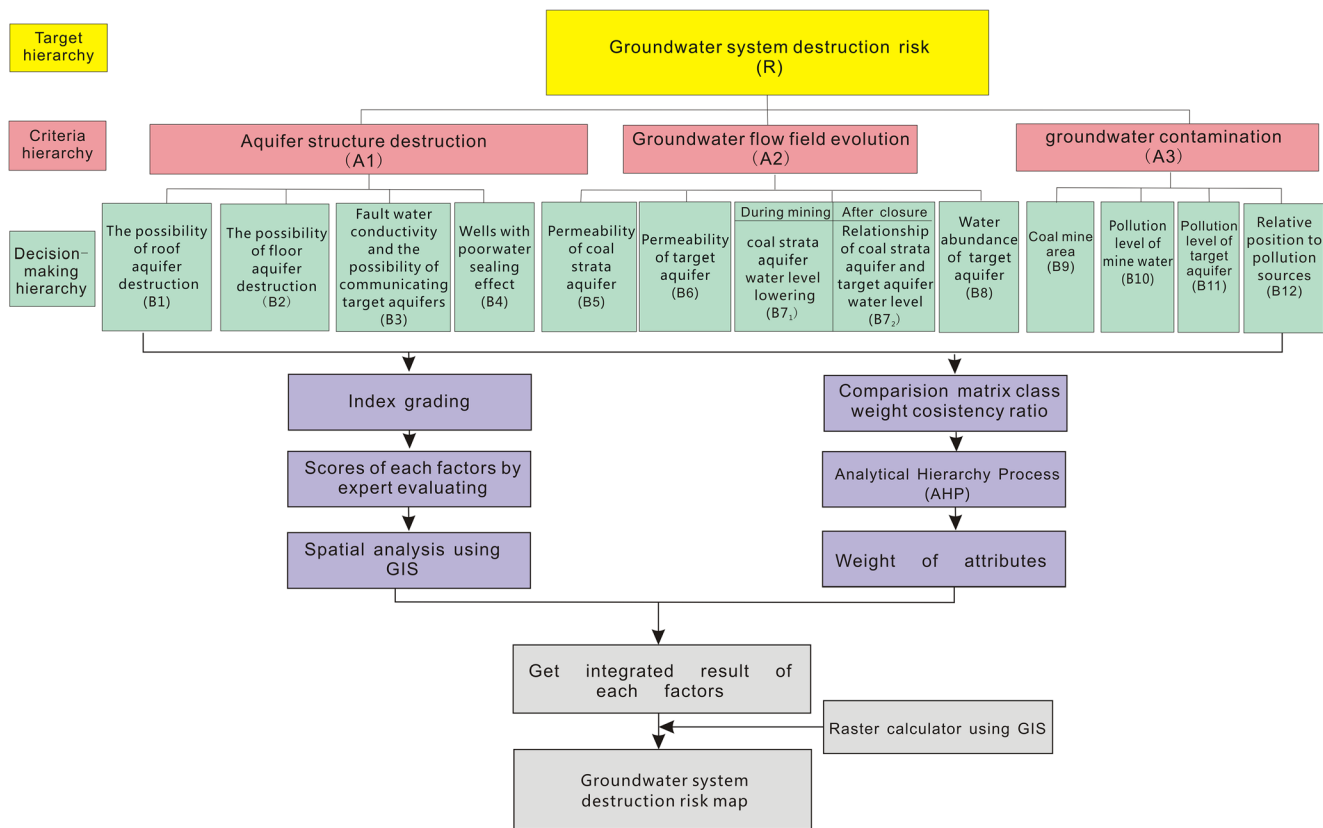


Fig. 10 Hierarchical structure of groundwater system destruction risk

Based on the weights of indexes calculated from the AHP judgment matrix (Table 5), the risk index model can be established at different stages of the coal life cycle, as follows:

$$\begin{aligned}
 R(\text{during}) &= \sum_{i=1}^n \alpha_i \times f_{B_i}(x, y) \\
 &= 0.1142f_{B_1}(x, y) + 0.1142f_{B_2}(x, y) \\
 &\quad + 0.0889f_{B_3}(x, y) + 0.0616f_{B_4}(x, y) \\
 &\quad + 0.0929f_{B_5}(x, y) + 0.0929f_{B_6}(x, y) \\
 &\quad + 0.1833f_{B_7}(x, y)1 + 0.1002f_{B_8}(x, y) \\
 &\quad + 0.0235f_{B_9}(x, y) + 0.0422f_{B_{10}}(x, y)1 \\
 &\quad + 0.0563f_{B_{11}}(x, y)1 + 0.0317f_{B_{12}}(x, y) \quad (3)
 \end{aligned}$$

$$\begin{aligned}
 R(\text{after}) &= \sum_{i=1}^n \alpha_i \times f_{B_i}(x, y) = 0.0444f_{B_1}(x, y) + 0.0672f_{B_2}(x, y) \\
 &\quad + 0.0499f_{B_3}(x, y) + 0.0922f_{B_4}(x, y) + 0.0767f_{B_5}(x, y) \\
 &\quad + 0.0553f_{B_6}(x, y) + 0.1069f_{B_7}(x, y)2 + 0.0767f_{B_8}(x, y) \\
 &\quad + 0.0763f_{B_9}(x, y) + 0.1040f_{B_{10}}(x, y)2 + 0.1298f_{B_{11}}(x, y)2 \\
 &\quad + 0.1207f_{B_{12}}(x, y) \quad (4)
 \end{aligned}$$

According to the above model, the risk index can be calculated in every grid. A larger value of risk index indicates a

greater probable occurrence of groundwater system destruction. The hierarchical risk index was analyzed using the GIS Raster Calculator. The spatial distribution values of 12 indexes were superimposed according to the above model (3 and 4). Finally, the composite spatial distribution maps of the GSDR during and after mining were obtained (Figs. 13 and 14), which were evaluated as three-level divisions of high-risk zone, less-high-risk zone, and safe zone (Table 6).

Figure 13 shows the GSDR of the Hongshan coal mine during the mining stage, including less-high-risk zone and safe zone, 23.83 km² and 44.07 km², respectively (Fig. 13). It indicated that the risk during mining was relatively low, with no high-risk zone. The risk was mainly manifested in the forms of groundwater funnel, coal seam roof, and floor aquifer destruction.

As shown in Fig. 14, the groundwater environment was threatened almost throughout the study area after mine closure, especially in the central portion of the study area—Luocun Town, with the high-risk zone of 10.73 km². There were water-conducting faults and wells with poor water sealing in this zone, which cause serious cross-strata pollution. Therefore, monitoring work must be strengthened, especially at the faults and contaminated wells. The less-high-risk zone was distributed in the periphery of the high-risk zone, with an area of 39.02 km². In this zone, groundwater was seriously polluted and the risk of contaminating groundwater was also

Table 5 Index system and classification of the main controlling indexes

Index (unit)	Reference	Groundwater environmental risk and index classification			Weight during mining	Weight after closure
		Low (1, 4)	Medium (4, 7)	High (7, 10)		
B1	“Three-below”(coal mining under buildings, water-bodies, and railways) coal mining regulation	Mining fracture zone away from the roof aquifer (> 10 m)	Mining fracture zone get close to the roof aquifer (2–10 m)	Mining fracture zone conducting the roof aquifer (< 2 m)	0.1142	0.0672
B2	“Three-below” coal mining regulation	Mining fracture zone away from the floor aquifer (> 10 m)	Mining fracture zone get close to the floor aquifer (2–10 m)	Mining fracture zone conducting the floor aquifer (< 2 m)	0.1142	0.0444
B3	Mining practice and experience	Water blocking fault, with a throw < 5 m, and low possibility of conducting the target aquifer	Water-conducting faults, with a throw at 5–10 m, and approaching the target aquifer	Water-conducting faults, with a throw > 10 m and high possibility of conducting the target aquifer	0.0889	0.0499
B4 (km)	“Technical guidelines for environmental impact assessment groundwater environment” (HJ 610-2011)	Influence radius ≤ 0.5	$0.5 < \text{influence radius} < 1.5$	Influence radius ≥ 1.5	0.0616	0.0922
B5 (m/day)	Empirical value	≤ 10	10~50	≥ 50	0.0919	0.0767
B6 (m/day)	Empirical value	≤ 10	10~50	≥ 50	0.0919	0.0553
B7	During mining, coal strata aquifer water level lowering were adopted. For closed mines, the relationship of mine water level and target aquifer water level was adopted.	Groundwater level drawdown < 5 m or below	5 m < groundwater level drawdown < 15 m or approximate	Groundwater level drawdown > 15 m or above	0.1833	0.1069
B8 (m ³ /day)	Statistics	≤ 500	500~1000	≥ 1000	0.1002	0.0767
B9 (km ²)	Statistics	Surrounding the mining area	Single seam coal mining area	Multilayer coal mining area	0.0235	0.0763
B10	“The Quality Standard of Underground Water” (GB/T 14848-2017)	I~III	IV	V	0.0422	0.1040
B11 (m ³)	“The Quality Standard of Underground Water” (GB/T 14848-2017)	I~III	IV	V	0.0563	0.1298
B12	Groundwater flow direction	Upstream	Lateral downstream	Downstream	0.0317	0.1207

high (Fig. 14). The safe zone was generally located in the southeast of the study area, which is the groundwater recharge zone, with an area of 12.51 km², and was less affected by the Hongshan coal mining (Fig. 14).

Social, economic and ecological vulnerability analysis and assessment

As discussed in “[Social-economic influence in coal mine life cycle](#),” the social, economic, and ecological negative influence of the Hongshan coal mine mainly appeared with the mine closure. Therefore, the SEEV analysis in this study was conducted at the stage of mine closure.

In the detailed analysis of existing data and other research results of socioeconomic structure, the vulnerability

assessment model was established, with seven main factors (Table 7). The seven factors are from the three aspects of social-economic-ecological destruction (D), fragility (F), and resilience (R). They include the proportion of available groundwater resource reduction (D1), the frequency and mode of residents exposure to poisonous and harmful groundwater (D2), the dependence on target aquifers (F1), the degree of local water shortage (F2), whether there are any alternative water sources or not (F3), the self-purification ability of target aquifers (R1), and the ability of socioeconomic adjustment (R2) (Table 7).

The vulnerability assessment model can be expressed as:

$$I = \delta D + \varepsilon F + \zeta R \quad (5)$$

where I is SEEV composite index; D is destructiveness index;

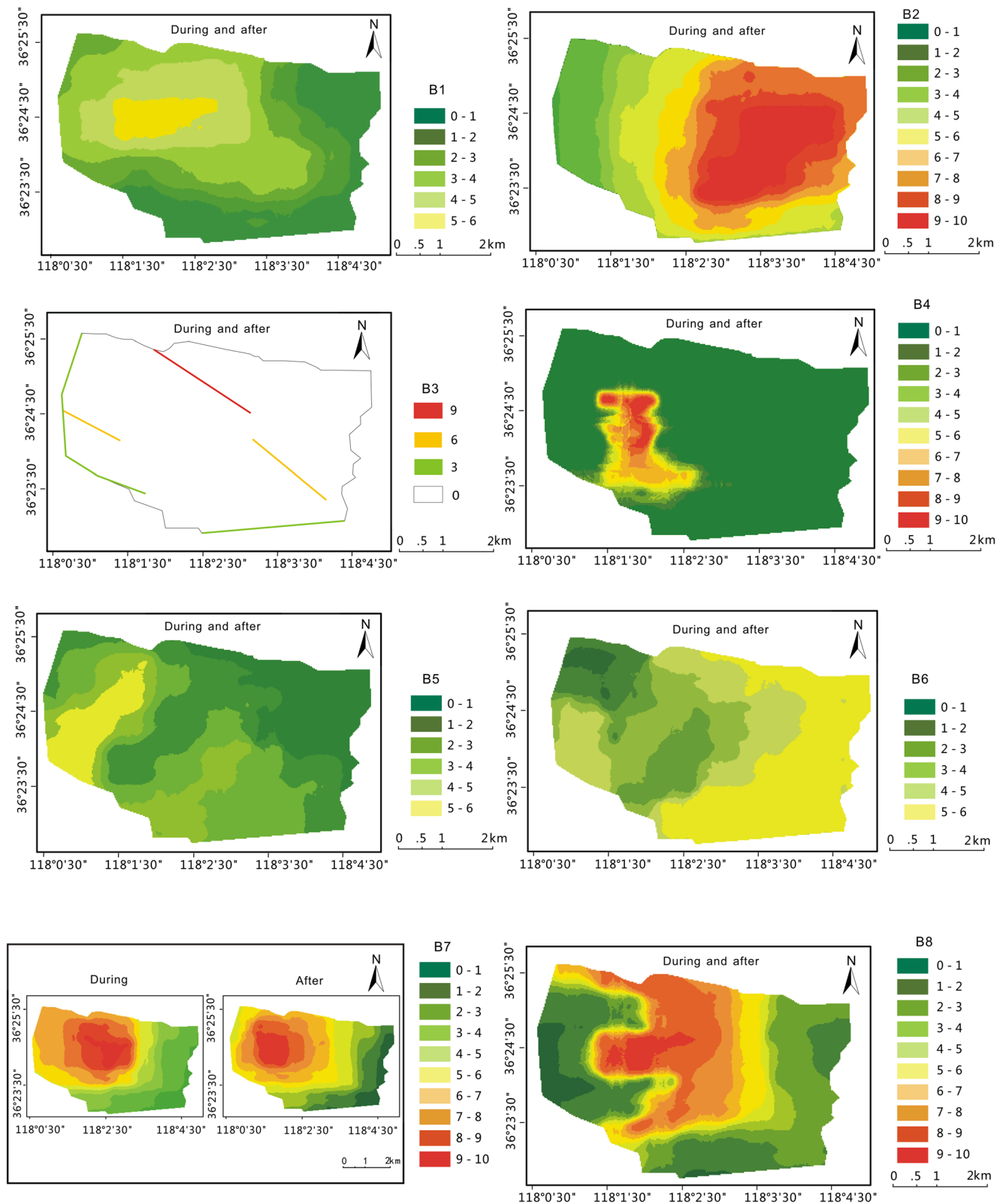


Fig. 11 Spatial distribution of B1–B8 factor score during and after the coal mining

F is fragility index; *R* is recovery capacity index, which consists of subordinate indexes: δ , ε , ζ which are the weight of each controlling factor (Table 7).

Similarly, seven evaluation indicators were graded by referring to industry regulations, expert advice, and statistics (Table 7). The weight of each index is determined by using

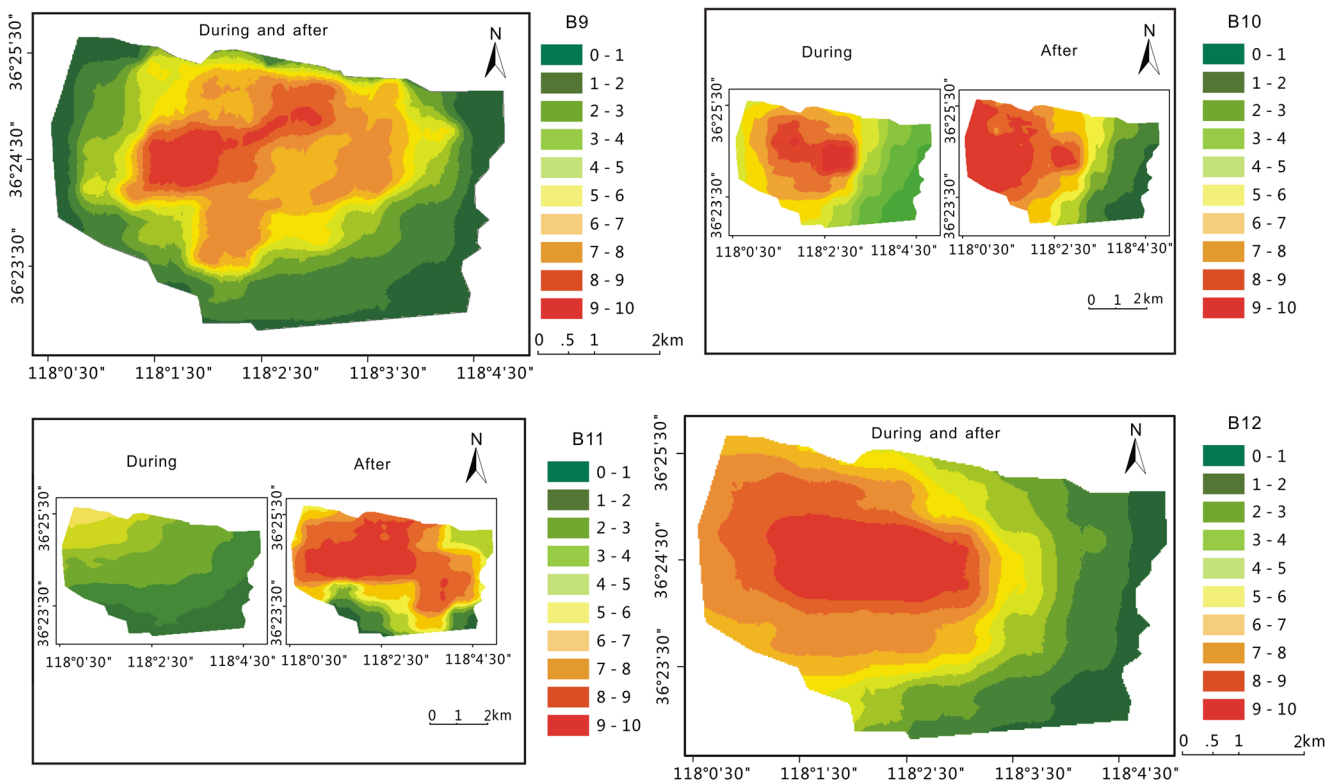


Fig. 12 Spatial distribution of B9, B10, B11, and B12 factors score during and after the coal mining

the AHP method (Table 8). Finally, the index was scored by expert scoring method, according to the data analysis of social, economic, and ecological environment status in the study area (Table 8). With the vulnerability assessment model (4), the comprehensive vulnerability index was calculated to be 8.55, which showed that the SEEV was high.

On the basis of all above analyses, the groundwater environmental risk was relatively low during the mining stage. However, there was a high GSDR after mine closure, and the local society, economy, and ecology were highly

dependent on the Ordovician limestone water, with high vulnerability. Therefore, the groundwater environmental risk in the life cycle of the Hongshan coal mine was dynamic, and the mine closure even increased the risk. The damage of land and water resources especially in high-risk area has seriously affected people’s lives and industrial and agricultural development, which directly or indirectly threaten people’s health and wealth. A survey according the ALARP standard showed that the individual risk in the study area is significantly higher than the acceptable risk level (Zhang 2013). Therefore, there is a

Fig. 13 Risk of groundwater system destruction during mining in Hongshan mine area

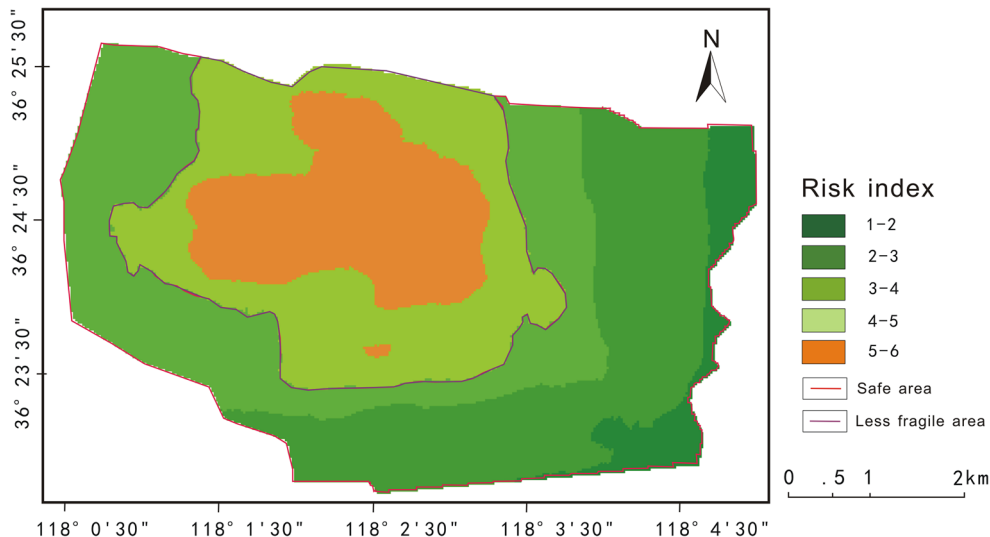
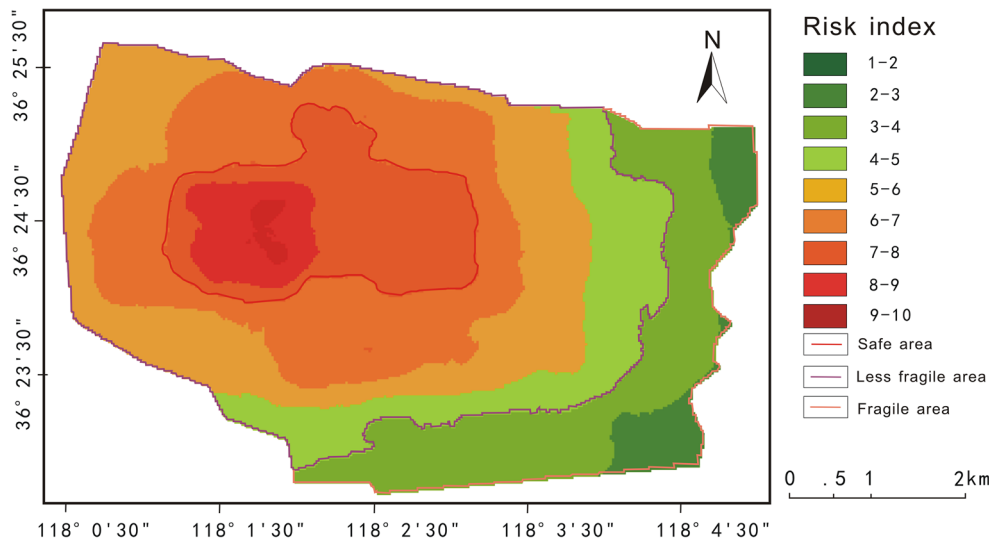


Fig. 14 Risk of groundwater system destruction after closure in Hongshan mine area



realization that how to manage environmental risks in an acceptable level and meet the needs of society during mine closing and post-closing periods is a critical factor of mine life cycle management.

Suggestions of groundwater environmental risk control

Pre-control of mine exploitation

The groundwater environment monitoring should be strengthened, especially where the risk is high. Moreover, the reutilization rate of mine drainage should be improved as much as possible.

Choosing a reasonable mining method

Mining methods with less damage to overlying strata should be selected firstly, such as filling method and partial mining method.

Plugging contaminated wells

In the Hongshan mining area, plugging engineering has been implemented for wells O12, O13, O20, O21, O22, O26, O28, and O33, with poor water sealing effect, and the effects were verified by a water pressure test. For similar coal mines that

have not yet been closed, it is suggested to check the sealing effect of the wells and block them timely.

Adjusting water utilization structure

The water utilization structure of society, economy, and ecology should be adjusted (Bui et al. 2019), and reducing the dependence of high-risk groundwater due to coal mining contamination (Fig. 8(e)). In addition, adjusting the water supply structure and improving the self-purification capacity of aquifers through artificial measures are also effective to mitigate the environmental risk of groundwater in coal mine areas (Escriva-Bou et al. 2020).

Conclusions

Based on the groundwater aquifer structure destruction, flow field evolution, and contamination analysis of each phase in the mine life cycle of the Hongshan coal mine, the framework for groundwater environmental risk assessment of the mine life cycle was proposed and assessed.

- (1) The Ordovician limestone water contamination after closure of the Hongshan coal mine is owing to cross-strata pollution from mine water, mainly through water conduction fissures, fault structures, and wells with poor water sealing effect. The results showed that about 50.23% of the study area belongs to the upper seriously contaminated zone. The contamination significantly reduced the amount of available resources, which has a negative impact on local social-economy sustainable development and residents’ health.
- (2) The GSDR assessment model was established, and 12 factors were determined. The mining area was

Table 6 Threshold of the partition of the groundwater system destruction risk

Risk index (<i>R</i>)	Risk level
$7 < R \leq 10$	High-risk zone
$4 \leq R \leq 7$	Less-high-risk zone
$1 \leq R < 4$	Safe zone

Table 7 Index system and classification of social, economic, and ecological vulnerability

Target hierarchy	Criteria hierarchy	Decision-making hierarchy	Reference	Vulnerability index classification and score		
				Low (1, 4)	Medium (4, 7)	High (7, 10)
Social, economic, and ecological vulnerability (I)	Destructiveness analysis (D)	D1	Expert advice	≤ 10%	10–30%	≥ 30%
		D2	“Exposure factors handbook” (EPA 2011)	Percutaneous exposure, bathing or swimming in contaminated water	Exposure through mouth, ingestion of contaminated plants, crops, fish, shrimp, shellfish, and other animals	Exposure through mouth, main drinking water supply source, or ingestion of contaminated plants, crops, fish, shrimp, shellfish, and other animals
	Fragility analysis (F)	F1	Statistics	Target aquifer water supply ≤ 20%	20% < target aquifer water supply < 50%	Target aquifer water supply ≥ 50%
		F2	“Per capita water consumption” (Whitman 1932)	2000 m ³ /person < per capita water consumption < 3000 m ³ /person	1000 m ³ /person < per capita water consumption < 2000 m ³ /person	Per capita water consumption < 1000 m ³ /person
		F3	Expert advice	Available and abundant	Available but shortage	Not available
	Recovery capacity analysis (R)	R1	Related literature (Jjemba 2005) and expert advice	High circulating speed	Slow circulating speed	Relatively closed aquifer
		R2	Compilation of water quota standards, laws, and regulations (China Standards Press 2006)	Focusing on the developing of finance, tourism, catering, education, and high-tech industries, with low water demand	Focusing on the developing of food, pharmaceutical, construction, and other industries, with medium water demand	Focusing on the developing of oil, power and mining, paper making, textile, chemical industry, etc., with high water demand

Vulnerability comprehensive index classification: low: $1 \leq R < 4$, medium: $4 \leq R \leq 7$, high: $7 < R \leq 10$

partitioned into medium- and low-risk zones during the mining stage, with areas of 23.83 km² and 44.07 km²,

respectively, which mainly reflected on groundwater funnels, coal seam roof, and floor aquifer destruction.

Table 8 The vulnerability index system and score of aquifer destruction in Hongshan mining area

Criteria hierarchy	Decision-making hierarchy	Study area parameters	Reference	Index classification	Score	Weight
Destructiveness (D)	D1	> 30%	(Fan 2007)	High	10	0.1174
	D2	Exposure through mouth, main drinking water supply source of residents	(Zhou et al. 2018)	High	10	0.3640
Fragility (F)	F1	56%	(Song 2007)	High	9	0.0580
	F2	The per capita water resource is 379 m ³	(Zeng et al. 2016)	High	9	0.0876
	F3	Available but shortage	(Guo et al. 2017)	Medium	6	0.1329
Resilience (R)	R1	High circulating speed and massive groundwater exploitation	(Sun 2016)	Low	3	0.0586
	R2	The secondary industry accounting for the largest proportion of 54.0% in local industrial structure	(Yu 2017)	High	8	0.1817

However, the risk increased after closure, mainly reflected on contamination, with the high-, medium-, and low-risk zones with areas of 12.51 km², 39.02 km², and 10.73 km², respectively.

- (3) The SEEV was expressed by its destructiveness, fragility, and resilience. Seven evaluation indicators were determined, and the social, economy, and ecology of the Hongshan mining area were highly dependent on Ordovician limestone water, with pretty high vulnerability.

There is a realization that mine closure even increased the risk, and how to manage it in an acceptable level during mine closing and post-closing periods is a critical factor of mine life cycle management. The results can provide effective support to the coal mine groundwater management, and a reference for the similar gradual geological environment problems in risk assessment.

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