Typical Cases of Groundwater Pollution and Control Strategies for Closed Coal Mine in China

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Keywords: closed coal mine, groundwater pollution, pollution pathway, prevention, control strategy

Posted Date: June 9th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-33797/v1

Abstract

Due to the coal resource depletion, complicated geological conditions, and policy adjustment of China coal mine industry, a large number of coal mines have been closed and abandoned. The rebound of groundwater level will cause flooding of goaf and roadways after mine closure. The hydrogeological conditions change significantly as well. The pollutants will leach out, transform and transport which lead to pollution and increase risk to the groundwater system in the mining area. This research investigated closed coal mining area in Xuzhou, Zibo, Fengfeng, Kaili, Yangquan, Doulishan, Huaibei, Jiaozuo, Jingxing, Mile, etc., to present typical cases for analyzing the featured pollutants in mine water. Eight groundwater pollution pathways were summarized in closed coal mines, including pollution infiltration from surface mining fissures; submerged water infiltration pollution; leaching pollution of surface solid waste; cross strata pollution from the diversion fissure zone in the mining roof; cross strata pollution through the mining fissures in the mining floor; cross strata pollution through the water-conducting wells; cross strata pollution of faults or collapse columns; water overflow from goaf. Three typical cases on cross strata pollution in the closed/abandoned coal mine were analyzed emphatically. Aiming at the prevention and control of groundwater pollution risk in coal mine, the technical ideas of reducing quantity and pollutant of mine water, channel blocking, extraction control, purification and utilization are put forward. Based on this idea, the main pollution prevention and control technologies are recommended, and the countermeasures for the environmental protection of groundwater in closed mine are proposed.

1 Introduction

China is the big coal producer and consumer in the world. Long-term intense mining has led to the depletion of resources in the old mining areas. At the same time, due to the increasingly complicated geological conditions and mining conditions, combined with industrial policies such as resource integration and de-capacity, a large number of coal mines have been abandoned, closed or integrated, and there will be more closed coal mines in the future. Therefore, the issues about resource reuse of the abandoned coal mines, mine safety, pollution prevention and control, and ecological restoration have received more and more attention (Feng et al. 2016; Huang et al. 2017; Wu and Li 2018; Yuan et al. 2018). Among the above problems, prevention and control of groundwater pollution is crucial for the recycling of coal mine resources, the groundwater system safety as well as the ecological protection.

Large-scale and long-term mining of coal mines results in a large-scale groundwater funnel centered on the mine well, thus the water cycle will reach a new balance. Once the mine is closed, the mine drainage system is shut down and the groundwater level rebounds, the dynamic, chemical and thermal fields of groundwater in the mining area could be changed consequently, which leads to a series of environmental hydrogeological problems. For example, water pollution and land subsidence have occurred in the Whittle and Shilbottie mines in the United Kindom (Adams and Younger 2001). In North China, the polluted groundwater by coal mining is about 2.7×109m^3 per year (Hu and Yan 2000), such as the Zibo coal mine area in Shandong (Wu 2013), the Yangquan coal mine area in Shanxi (Duan and Liang 2006), Kaili coal mine area in Guizhou, etc. Closed coal mine groundwater pollutants are complex, including inorganic pollutants, such as sulfate, iron, manganese, fluorine, heavy metals, etc. And the closed mines also contain trace toxic and harmful organic pollutants such as polycyclic aromatic hydrocarbons（PAHs） (Liu and Sun 2011; Bell et al. 2001; Feng et al. 2014; Moncur et al. 2014; Xu et al. 1998). Once the mine is closed, residual organic pollutants such as PAHs, benzene, and methylene chloride enter into the coal mine drainage (CMD), and gradually affect other mining areas through mining cracks, thus aquifers will be facing the pollution risk. In particular, most of the persistent organic pollutants (POPs) are toxic, or even mutagenesis, carcinogenesis and teratogenesis. Once the pollutants enter into the groundwater system, they will even affect the natural environment and ecosystems, as well transport to the food chain through drinking water and plant accumulation, eventually endanger the public health (Raza et al. 2017; Warężak et al. 2016).

Based on the investigation of more than 300 mined and closed coal mines, the main types of CMD in China are summarized in this paper. Groundwater pollution ways of the mining area are concluded. According to the analysis of typical groundwater pollution cases in closed coal mines, suggestions are put forward for pollution prevention and control, which will be available for the investigation, evaluation and treatment of groundwater pollution in coal mine area.

2 Main Pollution Components Of Coal Mine Drainage (Cmd) In China

Due to the different hydrogeochemical conditions in variety of coal mining areas, there are obvious differences in the water quality characteristics of mines. Even in the same mining area, the quality of CMD changes greatly with the mining depths and mining stages. Therefore, the types of pollutants in CMD varied. According to statistical analysis of more than 300 coal CMDs, China's CMD can be divided into the following main types, from the perspective of chemical composition.

(1) Acid CMD (A-CMD).

The pH of the CMD is less than 6.0, generally between 2.0 and 4.0. The lowest pH of the CMD is 2.5 in this survey. A-CMD is mainly located in Kaili, Maitreya, Yangquan, Zibo and other mining areas. The main formation mechanism is the oxidation of minerals such as pyrite in the coal seam. Therefore, A-CMD often contains high level of iron, manganese and sulfate.

(2) High -Concentration-TDS CMD (TDS-CMD)

The TDS-CMD is the CMD containing a TDS greater than 1000 mg/L. The results of this investigation show that the TDS of CMD in China varied in different mines, and could be up to 12080mg/L. TDS-CMD is common in arid and semi-arid mining areas in Western China. The mineralization degree of CMD in southwestern Shandong and Lianghuai mines is also very high. The salinity increased with the increased mining depth. Due to the problems of high treatment cost, the difficult disposal and poor recycling, the TDS-CMD has become an important environmental issue limiting the development of coal resources.

(3) High-Concentration-Sulphate CMD (S-CMD).

The S-CMD means the sulphate content of the CMD is more than 250mg/L. The sulphate content in the CMD can reach 8048mg/L in this study. In general, the oxidative dissolution of pyrite in the coal seam and sulphate in the coal and surrounding seams could form S-CMD. Meanwhile the ACMD and the TDS-CMD all contain high level of sulfate.

(4) High-Concentration-Heavy Metals CMD (HM-CMD)

The HM-CMD mainly contains iron, manganese, arsenic, lead, mercury, cadmium, etc., and occurs in the coal mines of Yunnan, Guizhou and Shanxi provinces. Iron and manganese are relatively ubiquitous. According to the investigation, the iron content is up to 1092mg/L. Generally, the A-CMD contains heavy metals. But some weak alkaline CMD contain high level of iron and manganese as well.

(5) Organic Contaminated CMD (O-CMD)

The O-CMD contains a variety of volatile organic compounds and semi-volatile organic compounds. Volatile organic compounds are low-carbon halogenated aliphatic hydrocarbons and substituted benzenes, such as methane, dichloromethane, cis-1,3-dichloropropene and toluene. And semi-volatile organic compounds mainly include nitrobenzenes, chlorobenzenes, PAHs and esters, and most of which are carcinogens. Sixteen kinds of preferential control of polycyclic aromatic hydrocarbons in CMD were detected in Xuzhou, Huainan, Zibo, Fengfeng and Zhangzhou. It was found that the content of polycyclic aromatic hydrocarbons in CMD was 0.56~4.61μg/L, with 3~5 rings. Polycyclic aromatic hydrocarbons are the main ones. Among them, the detection rate of low molecular weight polycyclic aromatic hydrocarbons such as naphthalene, anthracene, dihydroanthracene and phenanthrene is high. The main carcinogenic component is indeno[1,2,3-cd]pyrene, Dibenz[a,h] anthracene, and chrysene.

(6) Other CMD

Some other CMD that contains a large amount of fluoride, trace radioactive elements, etc. are also found in this study.

3 Groundwater Pollution Pathways Of Closed Coal Mines

Coal mines may cause groundwater pollution from exploration, mining to closure. Some pollution may even exist from the exploration stage to the long-term after closure. According to pollution sources and pollution channels, the groundwater pollution pathways of closed coal mine are generally classified into eight types (Fig. 1). The groundwater inrush or flooding channels in the mining process may also be the groundwater pollution channels after closure. Leaching drainage from the surface gangue piles, submerged water in the waterlogged area caused by coal mining subsidence and collapsed fissures underlying subsidence basin are the main pollution pathways of shallow groundwater. The three types of pollution may exist before closure, and if they are not effectively treated after closure, they will pollute the groundwater as well. After closure, the mine drainage will gradually be shut down, causing groundwater level rebound and water flooding in the roadway and goaf of the closed coal mine. When the rebound groundwater level is higher than that in the aquifer, pollutants in the mining drainage can infiltrate into aquifer and lead to the secondary pollution of groundwater through mining fissures in the roof and floor rock, water-conducting wells, faults or the collapse columns, and goaf. The following types are the main groundwater pollution pathways of the closed mine.

(1) Groundwater pollution infiltration from surface mining fissures: Surface fissures generated by coal mining in karst areas and bedrock mountains can become channels for groundwater pollution. The fissures at the edge of coal mining subsidence basins in mining plain areas can also lead to groundwater pollution.

(2) Submerged water infiltration pollution: In the eastern mining plain area of China, the groundwater level is very shallow, causing surface subsidence after coal mine, forming a large waterlogged area, which becomes the ubiquitous environmental issue in Huainan, Huaibei, Xuzhou, Yanzhou, Jining and other mining areas. Submerged water quality is very vulnerable to the external pollution sources, and then results in pollution of the surrounding shallow groundwater.

(3) Leaching pollution of surface solid waste: Pollutants infiltrate into the shallow groundwater under the precipitation leaching in the gangue and fly ash piles, which occur in Fushun, Fuxin, Yangquan and other mining areas.

(4) Cross strata pollution from the diversion fissure zone in the mining roof: Coal mining causes great damage to overburden rock and forms diversion fissure zone. When the coal mine closes and draining shuts down, the groundwater level rebounds and the pollutants in the mine move with groundwater. The pollutant migration causes cross strata pollution of the overlying aquifer, and even the pollution of the Quaternary unconsolidated aquifer, such as the Jiazhou mining area in Xuzhou.

(5) Cross strata pollution through the mining fissures in the mining floor: Coal mining causes damage to the floor rocks and promotes fissures development, which connects the pit and the floor aquifers. If the groundwater level of the floor aquifers is lower than the rebound groundwater level of the closed mine, the mine water will contaminate the aquifer.

(6) Cross strata pollution through the water-conducting holes: At the coalfield exploration and production stage, a large number of wells need to be constructed, including geological wells, hydrogeological wells, water drainage wells, gas drainage wells, and residential water supply wells, etc. This could be available for conducting different aquifers and result in the cross strata pollution if the pollutants transport through the poor-sealed wells. This case was found in Hongshan coal mine of Zibo coal mining area.

(7) Cross strata pollution of faults or collapse columns: faults or collapse columns are important channels for water inrush in coal mining. After the coal closure, the groundwater level rebounds, and the mine water carries pollutants to charge the water-filling aquifer, causing groundwater pollution.

(8) Water overflow from goaf - secondary infiltration pollution: the goaf water overflows to the surface perennially or seasonally, and then infiltrates into the groundwater causes groundwater secondary

pollution, such as the groundwater pollution cases in the Shandi River and abandoned coal mines pollutions of Yangquan mining area in Shanxi province and the Yudong River and abandoned coal mines pollutions of Kaili mining area in Yunnan province.

4 Typical Cases Of Groundwater Pollution And Control Strategies For Closed Coal Mine

4.1 Groundwater pollution of closed coal mine at Yangquan, north China

Shandihe watershed, with area of 58km2, located at central section of Niangziguan spring basin, Yangquan of Shanxi province of North China. The stratigraphic texture includes Carboniferous–Permian period coal seam and Ordovician period karst aquifer. In this area 28 coal mines were closed from 2005. Abandoned mine goaf were flooded by mine water and the acid mine water outflow of the surface and discharge to Shandihe River. The monitored data of groundwater flow and quality show that the average flow is 7842.79m^3/d, pH value is 2.39～6.58, TDS is 2382～11545mg/L, SO_4^{2-} is 1639～8048mg/L, total Fe is 666 mg/L, and Mn is 41.8mg/L, which significantly exceed the Chinese national standard for groundwater quality (Fig. 2).

In this case, the goaf water outflowed to the surface and then infiltrated into the karst aquifer of Ordovician period (Fig. 3). The leakage rate was 61.4% approximately. Leakage of goaf water had heavily polluted groundwater and water wells for local villages were shutoff.

Because of the infiltration of polluted water the Niangziguan Spring water quality declined remarkably in past decades. According to previous survey (Yang 2017), from the year of 1986 to 2012, TDS of the Niangziguan Spring water increased from 500mg/L to 1100 mg/L. SO_4^{2-}increased from 200mg//L to 350mg/L. Sulfur isotope, contributing from coal seam, increased 2.07～6.14% per year from 2003 to 2014 (Liang et al.2017; Huo et al. 2015).

4.2 Groundwater pollution of closed coal mine at Zibo, east China

Coal seam of Carboniferous–Permian period was mined at Zibo coal basin of Shandong province, East China. In 1992 the mines were closed and the goaf water level rebound from -200m (1992) to +35m (1995) of elevation, which was 10～20m higher than Ordovician karst aquifer water level. Till 2003 the mine water level had risen to +68m. Geophysical exploration, groundwater tracer experiment, as well as isotope testing were used for groundwater chemistry investigation (Zhang 2016; Zhang et al. 2016; Zhou et al, 2018). Ordovician groundwater level of three well rose from +5～10m (before closure) to +65.5m (after closure). Combined with hydrochemical analysis the Ordovician karst groundwater was polluted by the goaf water of closed coal mines. The contaminated area was 49.2km^2. The typical pollutant chemicals were TDS, SO_4^{2-} and total Fe. TDS varied from 1000 to 2171.9mg/L, SO_4^{2-} was 800-1443.9mg/L, and total Fe was 2.7 ~4.3 mg/L.

4.3 Groundwater pollution of closed coal mine at Kaili, southwest China

Yudonghe catchment belongs to south west karst geological unit. Coal seam distributes in Permian system. The upper aquifer of coal seam is P_1q- P_1m limestone aquifer with sinkhole, vertical fissure and karst collapses. Mining-induced water-conducting fissures is also the pathway of precipitation infiltration into mine area. Investigation showed that more than 100 coal mines were closed or abandoned and A-CMD discharged to Yudonghe River from abandoned gallery or karst underground river. The A-CMD flow volume was 3091-9842m^3/h, with pH value of 2.78(lowest), SO_4^{2-} of 3430mg/L(highest), total Fe of 800mg/L(highest), and Mn of 2.3mg/L(highest).

Field investigation showed that 21 springs distribute in the mining area and 12 springs were polluted. Fig. 5 shows the geologic condition of Longdong spring. During raining reason the mining tunnel was flooded by A-CMD and mine water flowed to the spring along underground river, fracture, and mining-induced fissures.

5 Suggestions For Closed Coal Mine Groundwater Protection In China

The above typical cases show that the closure of coal mines has already resulted in pollution to the groundwater system in the mining area. With the increase of closed coal mines, the pollution area could be further expanded, and the pollution intensity could be further enhanced. However, there is still a lack of research on issues of pollution mechanism, prevention technology, regulations, etc. Some suggestions should be presented

(1) Conducting investigation and risk assessment of groundwater pollution in coal mines

The idea of economic development but neglecting mine closure should be changed. The concept of green mine closure should be established and implemented. In addition, the reasons of closure (i.e., resource depletion, policy closure, permanent closure or temporary closure) must be distinguished, and the groundwater pollution conditions must be investigated. Clear risk assessment, environmental risk and control requirements, pollution prevention and control measures must are proposed. Especially for closed mines with significant environmental risks should be monitored and assessed for a long period of time.

(2) Establishing a groundwater monitoring network for closed coal mine

The closed coal mine information management system needs to be established, which includes the environmental problems investigation (e.g., surface water pollution, groundwater pollution, soil pollution, ecological damage, etc). Especially, a groundwater environmental monitoring network for closed mines with outstanding water environment problems are needed. Groundwater monitoring technical requirements and data management responsibilities need to be clarified as well.

(3) Formulating technical specifications for investigation and evaluation of groundwater in coal mines in China

According to the ‘Mineral Resources Law of the people's Republic of China’, ‘Environmental Protection Law of the People's Republic of China’, ‘ Law of the People's Republic of China on the Coal Industry’, ‘Law of the People's Republic of China on Environmental Impact Assessment’, ‘Provisions on the Protection of the Geologic Environment of Mines’, ‘Detailed Rules for Water Prevention and Control in Coal Mine’, technical standards for groundwater environment investigation, environmental impact assessment and pollution control technique should be formulated. And the ‘Specifications for Compilation of Geological Report of Solid-Mineral Exploration/Mine-Closing’ and the ‘Technical Specification for Monitoring and Distribution of Groundwater Pollution in Abandoned Mine’ should be modified in time.

(4) Establishing China's closed coal mine groundwater pollution prevention and control technology system

The prevention of groundwater pollution in mine closure should be prior to pollution remediation, due to the fact that pollution control and restoration are extremely difficult. It is recommended to adopt the technical idea of “drainage reducing, pollution reduction, channel blocking, pumping, purification and utilization” to form a aboveground-underground prevention and control combined technology system, including CMD reduction, pollutants reduction, underground engineering treatment, hydrodynamic field control, pollution channel plugging, CMD purification and utilization, etc., in order to achieve the protection and sustainable use of water resources in mining areas.

Declarations

Funding “the National Natural Science Foundation of China” (41572218, 41472223, 41672253) and “the Chinese Public Welfare Research Funds for Environmental Protection Industry” (201109011).

Competing interests Authors declare no competing interests.

Data and materials availability All data is available in the main text.

Code availability Not applicable.

Authors' contributions Qiyan Feng: article idea design, data collection, article writing. Lai Zhou: article writing, article review. Yongping Liang, Jianwei Zhou, Hujun Ren and Ping Lu: data collection, the English polish of the article, suggesting constructive amendments to the article. All authors agree to submit the article.

Acknowledgements We gratefully acknowledge financial support from both “the National Natural Science Foundation of China” (41572218, 41472223, 41672253) and “the Chinese Public Welfare Research Funds for Environmental Protection Industry” (201109011).

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Figures

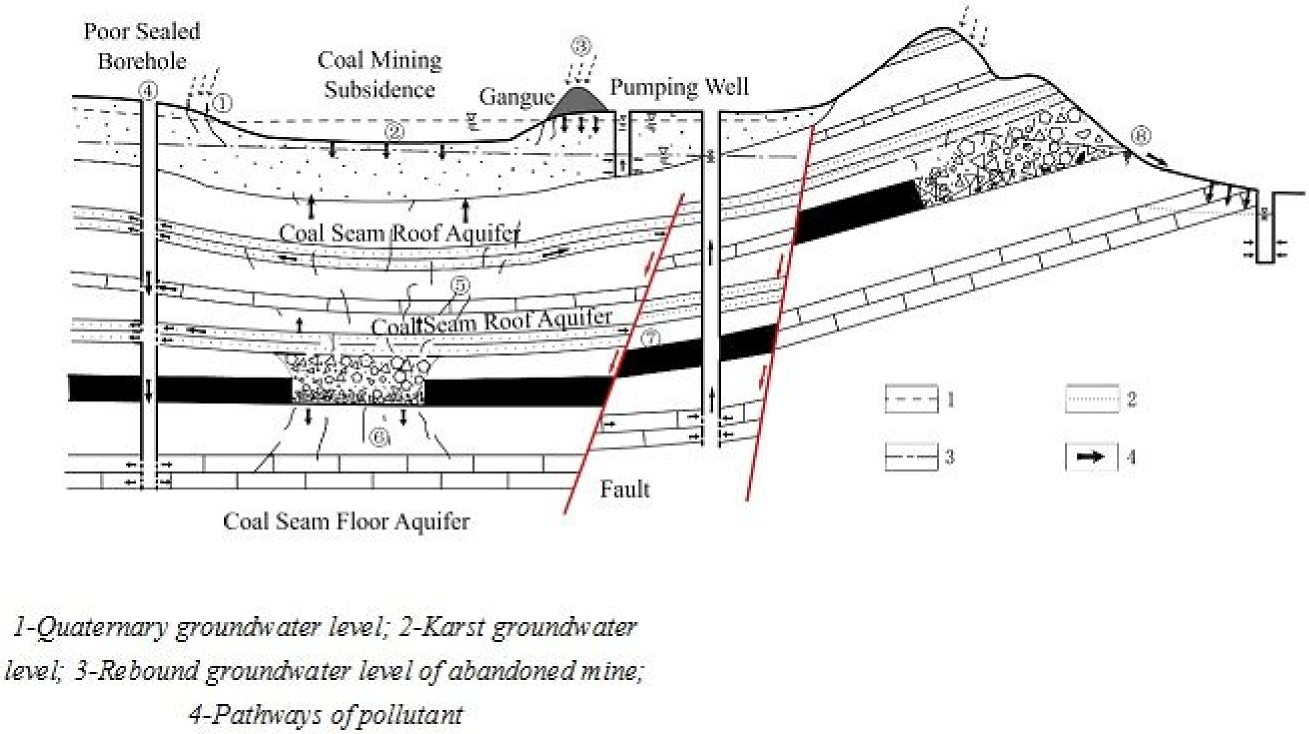


Figure 1

Schematic diagram of groundwater pollution pathways in closed mine

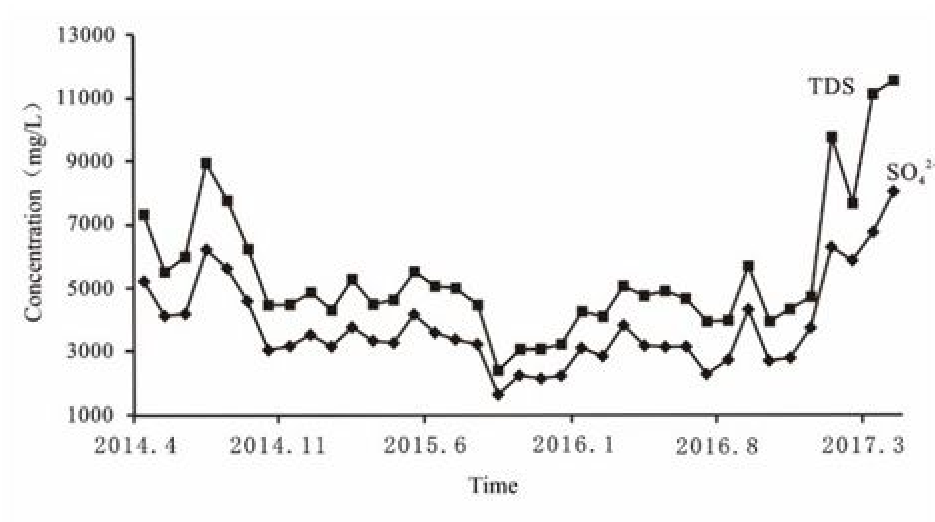
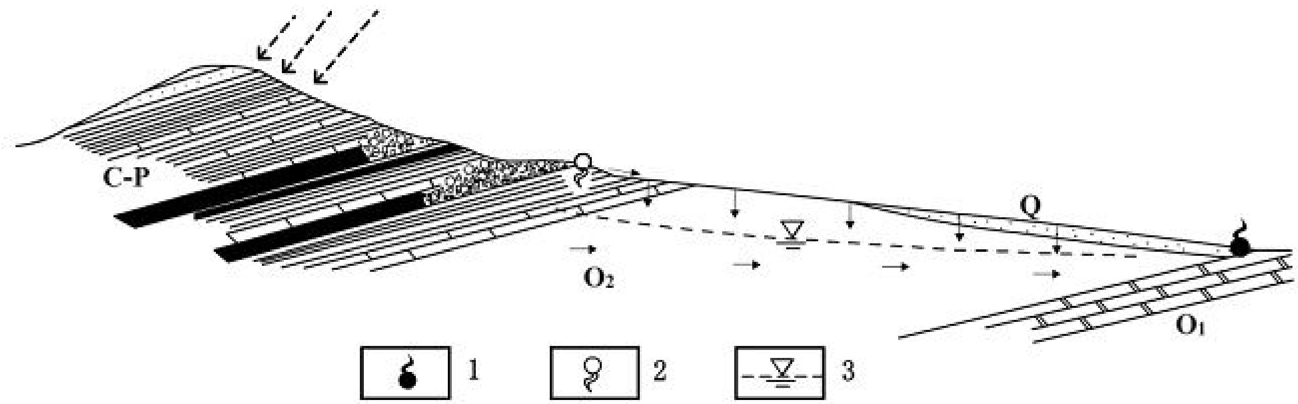


Figure 2

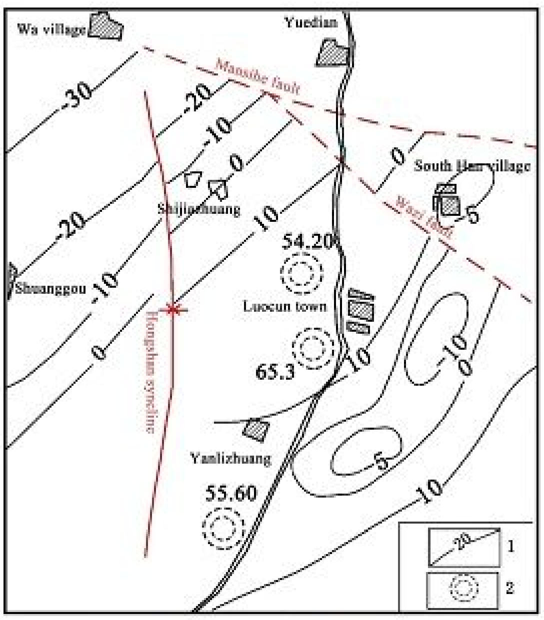
Variation curve of TDS and SO42- in goaf water



1-Karst spring; 2-Goaf water; 3-Groundwater level

Figure 3

Geological sketch map of the goaf water flow in Shandi River



1-Groundwater level contour; 2-Abnormal zone of groundwater level

Figure 4

Groundwater level in HongShan mining area after mine closure(June 2003)

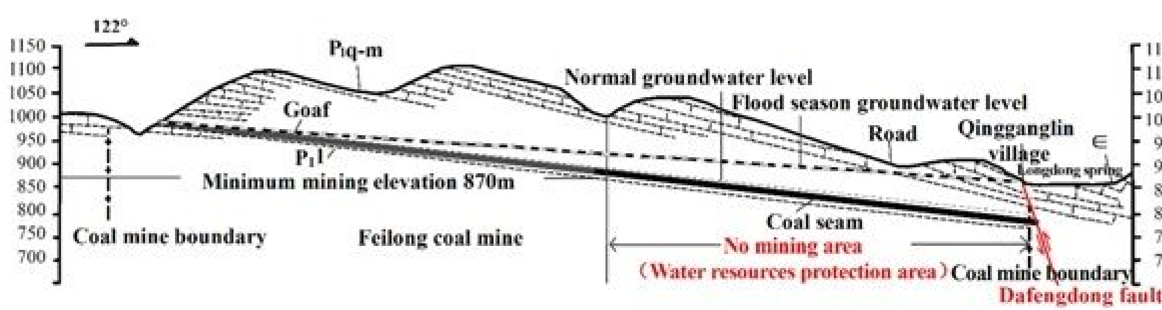


Figure 5

Pollution of Longdong Spring