Indexed in
Scopus Compendex and Geobase Elsevier,
Geo-Ref Information Services-USA, List B of Scientific
Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 05

October 2016, P.P.1863-1868

A Review of Technological Development in Water Hazards Control in China Coalmines

HERONG GUI[1, 2], D VENKAT REDDY[3] AND LINHUA SUN[1, 2]

[1]*School of Earth Science and Engineering, Suzhou University, Suzhou, Anhui, China, 234000;*
[2]*National Engineering Research Center of Coal Mine Water Hazard Controlling, Suzhou, Anhui, 234000;*
[3]*Department of Civil Engineering, National Institute of Technology Karnataka (NITK), Surathkal Srinivasnagar, Mangalore, DK, India*
Email: *hrgui@163.com, dvr1952@gmail.com, sunlinh@126.com*

Abstract: The complex hydrogeological conditions in China coalmines have created a number of inherent water hazards. In the over 60 years of efforts in water hazards control, rich experiences have been accumulated in technology engineering. This article focuses on the major development stages and illustrates current applications of the key technologies in hydrological drilling, grouting and water plugging, and geophysical and geochemical prospecting, as well as the direction for future development, which can provide reference and facilitate communications with coalmines under similar conditions across the world.

Keywords: *coalmine water hazards, water hazards control technology, water inrush mechanism, China*

1. Introduction

China has a long history in coal mining. As far back as in 1637, the prominent Chinese scientist, Song Yingxing, who compiled the Chinese encyclopaedia "Exploitation of the Works of Nature", recorded in great details of the ancient mining technologies, including prospecting, exploiting, excavating, scaffolding, ventilating, elevating, transporting, and gas drainage. From 1949, the coal mining industry in China embarked on a large-scale development. Mining technologies were upgraded and improved from manual excavation and blasting mining in early days to fully mechanized mining as of today. Meanwhile, hydraulic mining and open-pit mining are also developing at full speed, contributing to the phenomenal increases in coal output. At the beginning of the New China, national coal output was only at 32.4 million tons, in contrast to the 1 billion tons by the end of 1980s and the historical high of 4 billion tons in 2014 (Fig. 1).

Looking at the distribution of known coal resources in the mainland China, the over 500,000 km^2 of coal-bearing area is divided into six regions, namely North China Carboniferous and Permian, Northeast and Northwest Jurassic, South China Late Permian, Tibet-West Yunnan Mesozoic, and Taiwan Paleogene [1]. The bearing conditions and geological features in these regions are vastly different from one another, complicating mining difficulties with a variety of water hazards which posed serious challenges.

Among the top 5 major types of accidents in China coalmines (water, gas, spontaneous combustion, coal dust, and roof caving), water-incurred accidents are the deathliest and most destructive. Between 2000 and 2011, a total of 1,089 water-incurred accidents were recorded nationally, out of which 87 were classified as of massive destruction [2].

China's coal mining history is in nature a history of water hazards control. On 13 May 1935 in Zibo of Shandong Province, a horrifying water-incurred accident shocked the world by killing 538 people in the Beida coalmine, which was built by France in 1904. Ever since then, China coalmines are inflicted with such accidents and the search for effective counter measures has never ceased. Especially in the 60 years after the founding of the New China, the central government called upon coalmining industry to strive for "high yield, high efficiency, and safe production". Motivated by government directive, coalmining companies strengthened industry-university-research cooperation and initiated significant researches on applicable and scalable technologies against water hazards of grave threats. The experiences gained in the 60 years and stages in technological development will undoubtedly be of reference to other coal-producing countries afflicted by water hazards.

2. Continuous Improvements to Water Hazards Control System

Starting from the 1950s, researches in China have progressively resulted in a scientific and disciplined system for water hazards control.

2.1. Exploratory Stage (1950s)

In the 1950s, following the founding of New China, there were no sufficient technological capabilities in hydrogeological researches in the country. Nor were there standards or policies to follow regarding water hazards control. In the second half of 1950s, the government sponsored a large number of students to major in geology and hydrogeology, who would later join coalmining companies after graduation and led the early efforts in water hazards control. The focuses of their efforts were to prospect and drain underground water through drilling, carry out complementary hydrogeological exploration in coalmine (pit), and monitor hydrogeological dynamics, etc [3].

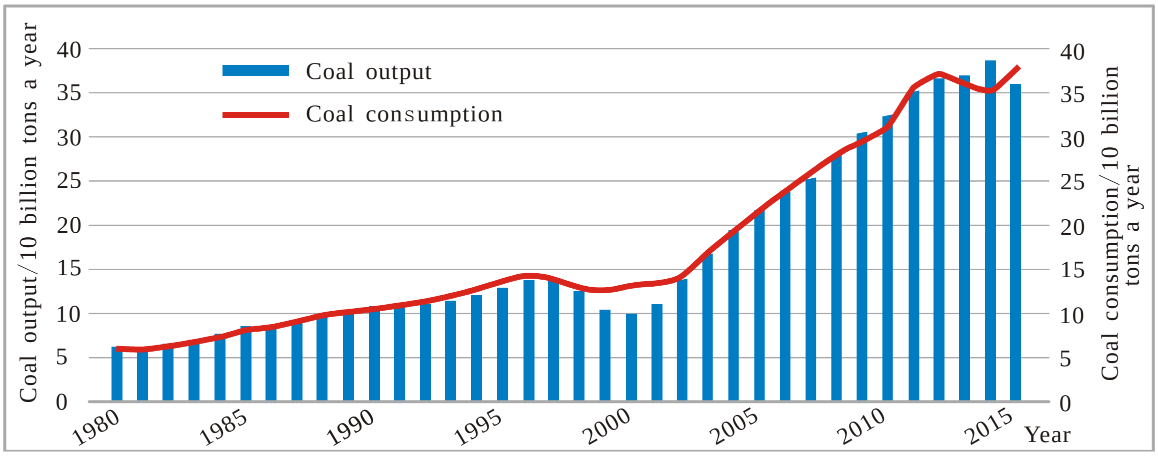

Fig. 1 *Coal output and consumption in China over last 30 years (According to the NBS of China)*

2.2. Development stage (1960s~1970s)

In the early 1960s, the government set up a number of research institutes specializing in hydrogeology, mining under water bodies, grouting and water plugging, etc. Through industry-university-institute cooperation, the aim was to experiment and find solutions to control major water hazards, to cultivate and train specialists for mining operations, and to provide talent and technical support for safe production and new coalmines development. In 1964, the government chose Jiaozuo Dashui coalmine in Henan Province as a study subject and launched a nationwide research on its hydrogeological features. Experts in the field were tasked to find out the pattern of coalmine water inrush and pinpoint the relevant hydrogeological parameters, such as water inrush coefficient and unit inflow.

(1) Water inrush coefficient (T_s) refers to the maximum hydrostatic pressure that floor coal seam aquifuge of 1-metre thick can withstand when mining over pressurized water, i.e. $T_s = P/M$ (M is the thickness of the floor coal seam aquifuge in metres; P is the head pressure of the pressurized water exerted on the bottom of the aquifuge in Mpa). The value of T_s is a critical parameter to evaluate the probability of water inrush in the floor coal seam [4-5]. It was then written into the Coalmine Hydrogeology Protocol, a legally binding document.

(2) Unit inflow (q) refers to the ratio between pump output in a certain drill (*Q/L/s*) and the corresponding drawdown (*s/m*). In one set of pumping tests, a diagram of $Q=f(s)$ (Fig. 2) can be obtained by taking variable pump outputs Q_i (i=1, 2, 3…) and corresponding drawdowns s_i (i=1, 2, 3…). Mark the value of Q_{10} produced by a drawdown of 10 meters, then the water abundance of the aquifer is evaluated by $q=Q_{10}/10$ (Table 1).

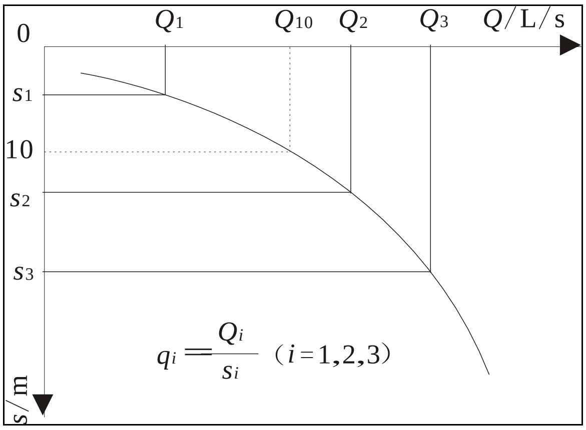

Fig. 1 *Schematic diagram of Q=f(s) [2]*

Table 1 *Grades of aquifer water abundance [2]*

Grades of aquifer water abundance	Unit inflow *q* (L/s·m)
very high	>5
high	5~1
medium	1~0.1
low	<0.1

In addition, in the latter half of 1970s, deformation patterns of overlying rock strata were spotted in coalmines across the country. Theoretical analysis showed a consistent stratification of three layers post-mining, respectively from bottom up are caving layer, water-conductive fissure layer, and block shift layer [6-7]. The abundant research achievements guaranteed effective control of water hazards in the upper part of coal seam.

2.3. Establishment of regulations (1980s)

Starting from 1980s, the accelerated economic development boosted the scaling-up of coal mining industry. With developments and upgrading of coalmines old and new, accidents caused by water inrush increased significantly, calling for immediate actions in water hazards control. In response to the severe situation, the government advanced the establishment of regulations for water hazards control. The Coalmine Hydrogeology Protocol enacted in 1984 [8] formalized for the first time the classification of coalmine hydrogeological conditions. It also set specific requirements for complementary hydrogeological exploration, water hazards detection and accident prediction, as well as mapping standards of all essential documents for hydrogeological analysis. In 1985, the Protocols for Coal Pillar Retainment in Major Roadways and Compressed Coal Mining under Buildings, Water Bodies, and Railways, or known as the Mining Protocols for Three Underground Scenarios [9], was promulgated to standardize the retainments of water-resisting (sandstone-resisting and anti-collapse) coal pillars under different water bodies. In 1986, the Protocols on Coalmine Water Control [10] was issued to enforce strict requirements on leadership and accountabilities, technical management, foundation work, technical standards, approval processes, and incentives and punishments. All of the legislations provided work principles, legal regulations, and technical references to facilitate the engineering and detection of water hazards control, as well as the efforts to understand water inrush mechanism. The discovery of the three layers in post-mining floor coal seam was one of the many outstanding achievements in this period. Through numerous samplings and numerical modelling, the Chinese experts discovered that three layers would appear in the floor coal seam post-mining: floor fracture layer, intact rock layer, and rising pressurized water along fault zone. The depth of floor fracture layer (h_1) is in direct proportion to the length of the sloping panel (l) [11-12] as shown in Fig. 3. Due to the impact of h_1, the thickness of floor coal seam aquifuge will decrease while the water inrush coefficient (T_s) increases, aggregating the danger of imminent water burst in floor coal seam.

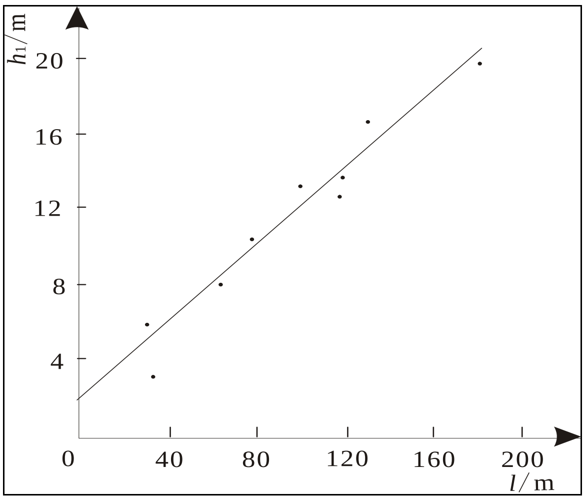

***Fig. 2** Correlation between depth of floor fracture layer and length of sloping panel [12]*

2.4. Improvements stage (since 1990s)

The 1990s marks the skyrocketing development of China economy whose demand for coal grew significantly (Fig. 1). With the introduction of fully mechanized mining technology, water hazards control in coalmines was tested for higher standards. At national level, the earlier enactments, Coalmine Hydrogeology Protocol and Mining Protocols for Three Underground Scenarios, were constantly revised and updated. Based on the previous version of Protocols on Coalmine Water Control, the authority established the Regulations on Coalmine Water Control [13] in 2009. The Regulations outlined the basis for classifying hydrogeological conditions in coalmines into grades of simple, medium, complicated, and extremely complicated. Requirements for each grade on technical management, engineering facilities, and water control equipment were all clearly defined.

(1) Essential conditions for mining on floor pressurized water: if the aquifuge in floor coal seam is fractured by faults or other tectonic structure, T_s shall not be bigger than 0.06Mpa/m; if not fractured, T_s shall not be bigger than 0.1Mpa/m. Other than the two conditions, water control engineering is mandatory to maintain T_s within the required range. Available measures include draining to lower head pressure of the pressurized water or solidifying the aquifuge by grouting [14-15].
(2) Reclassifying hydrogeological conditions every three years. For coalmines with complicated and extremely complicated grading, submersible pump and compatible drainage facilities are mandated at the bottom of the shaft. The purpose is to drain off waterlogging in case of massive inrush, so that the cage can function properly.

The underground water invading coalmines could be as safety menaces as valuable resources. Therefore, the prevailing thought is to combine water hazards control with water resource utilization [16]. If regular water inrush is above 100m^3/h, the coalmine operation is obliged to perform water treatment to recycle the water for other uses in coal washing, underground coalmine production, fire water, landscaping, and power plants. Legislation is already in process which demands for a 70%-above multi-purpose utilization of coalmine water and new projects shall prioritise the use of coalmine water for production.

3. Developments and Applications of Key Technologies in Water Hazards Control

At the end of 1980s and the first years in 1990s in particular, the key technologies in water hazards control, such as drilling and grouting, had been the focal points for research and application in China. Technical achievements guaranteed the realization of "high yield, high efficiency, and safe production" in extremely complicated hydrogeological environments.

3.1. Hydrological Drilling

Two types of drilling technologies are in use to probe water hazards in coalmines, underground and aboveground drilling. Prior to 1990s, conventional rotary drilling was the prevailing method. Since 2000, the focus shifted to directional drilling, which can take measurements in real-time and control precisely along the drilling track, allowing accurate positioning or targeting in a specific stratum [17-18]. As of today, the technology has evolved into a number of techniques for various purposes and wide applications in coalmine water hazards control, including accurate positioning and deflecting branch drilling, quasi-horizontal directional drilling for long distance underground, directional aboveground drilling of large calibre, etc. In addition, developments in relief and rescue technologies have brought in large-scale submersible pump and drainage, express drilling, large calibre drilling, and speed grouting. More noticeably, the emergency drill rig comparable to the SCHRAMM T-series carrier mounted drill rig is now available for industrial applications.

3.2. Grouting and Water Plugging

Starting from the early 1950s, development focus was to block inrush points by grouting at hydrostatic level using single liquid cement. In the late 1950s, this hydrostatic grouting technique was deployed to repair the longstanding inrush points from pre-New China era and production resumed to normal in those flooded mines. In the early 1960s, Single liquid cement was applied for ground pre-grouting before excavation. In order to achieve grouting under hydrodynamic conditions, quick-setting materials, such as cement-sodium silicate slurry and chemical grouting, were developed in the late 1960s and widely used in large and medium-scale curtain closure and hydrodynamic grouting of major inrush points. Since 1980s, hydrodynamic grouting was in full application to resume flooded mines and to solidify and reinforce the aquifuge in floor coal seam [2].

3.3. Geophysical Prospecting of Water Hazards

Drilling supplemented by geophysical prospecting had been the dominant method to prospect water hazards in China coalmines during 1950s and 1970s. Imported equipment, such as SSS-1 explosion-proof seismometer from Hungary, geo-electric instrument from Canada, and high-resolution seismometer from the US and France, were introduced in 1980s. At the same time, China also independently developed ground penetrating radar (GPR) for underground prospecting, roadway scenographer, and digital DC prospector. After 1990s, technologies for both above and underground prospecting had major breakthroughs. For aboveground geophysical prospecting, new technologies utilized 2D and 3D seismic prospecting, transient electromagnetics method (TEM), high-density electrical prospector, direct currents prospector, controlled source audio-frequency magnetotellurics (CSAMT), GPR, Rayleigh wave and inter-borehole prospecting. For underground geophysical prospecting, new technologies utilized ratio wave penetration, TEM, direct currents prospector, high-density electrical prospector, GPR, audio-electrical penetration, and channel wave seismic detection. All of the technologies had greatly improved the efficiency and accuracy in water hazards detection [2]. New seismic apparatuses are being developed to realtime monitor water hazards in a radius of 10-50m around the drilling, excavation and mining locations by analysing seismic activities caused by drilling and excavation.

3.4. Geochemical Prospecting of Water Hazards

After entering 1960s, the coalmine research turned to the geochemical impact of underground water in coal seam. Conventional hydrochemical indicators were used as basis for identifying possible sources of water inrush.

A water inrush accident happens when the water bursts abruptly into the pit at a high speed exceeding the drainage power of all facilities, thus flooding work space, roadways, or mining area and drowning people to injuries or deaths. However, there are always indicators of such accidents beforehand. The changes of water volume generally go through stages of “moist-dripping-sprinkling-flowing-bursting” [19], as illustrated in Fig. 4. The transition in “moist-dripping-sprinkling-flowing” is called pre-warning.

In the 1990s, based on the interaction pattern between water and rocks, numerous tests were taken out on the geochemical properties of coalmine aquifers and underground water, including conventional hydrochemistry, microelements, and environmental isotopes. Through factor analysis and other methodologies [20-22], all of the data were formed into an identification model [23-25] to trace the evolvement of underground water system affected by mining activities and to capture hydrochemical changes during the pre-warning stages in a timely fashion. If it identifies a highly pressurized aquifer as the water source, proactive measures must be taken in advance to lower risks of water accidents.

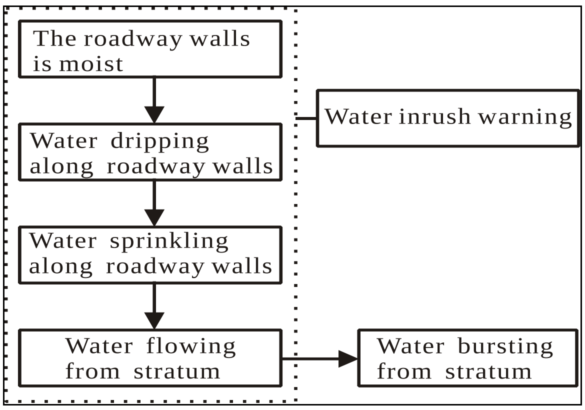

Fig. 3 *Pre-warnings to water inrush [19]*

3.5. Water Disaster Forecast and Pre-Warning Technology

A new era of water hazards control in China coalmines is unfolding as digital and information technologies taking on more importance. Having established a system of indicators on water hazards, the monitoring facilities are organized in an intelligent and web-based structure. Sensors of all kinds are deployed around the mining area and feedback realtime data of stress, seepage, temperature, hydrochemical status and so on into cloud-based platforms. Meanwhile, historical data from geological and hydrogeological prospecting and from past water accidents are centralized in databases for further data mining and analysis. By combining existing and current information, a forecast and pre-warning model is built to effectively manage water hazards and prevent accidents of all magnitudes.

4. Direction for Future Development in Water Control

There are over 30 types of water hazards in China coal mine. Through research and trials in the past six decades, most of the water hazards have been effectively contained. At present, however, there are some types, including pore water and karst water, remain to be the culprit of severe disasters that cause human casualties and huge economic losses. They are the major detrimental water hazards in today's coal industry and the key areas for technological breakthroughs in future researches.

(1) Pore water above coal seam, karst water in the thick limestone beneath coal seam, water in karst collapse pillar, goaf water，water in separation layers and other major water hazards confronting coalmine production shall be the focal points in research on inrush mechanism and R&D on comprehensive technologies in water control [7].

(2) The R&D on forecast and pre-warning system of the major detrimental water hazards shall build on the findings from water-rock interactions and data from hydrological and geochemical studies on underground water, so as to identify the multiple hazards in one water inrush both qualitatively and quantitatively.

5. Conclusions

From the above analysis, conclusions can be made as follows:

(1) China started the foundation work on coalmine water hazards control in the 1950s and cultivated a generation of specialists by selecting Jiaozuo Dashui coalmine in Henan Province as the test field for research and practice. In 1980s, a comprehensive system of regulations and protocols for water control was set up at national level, which was continuously revised and updated throughout 1990s. At current stage, legislation is focused on water hazards control and water utilization in coalmines.

(2) As regulations on water control matured and formalized since 1980s, researches on technology and theory in this field were elevated to new heights. From traditional rotary drilling to directional long-distance drilling and deflecting branch drilling, from hydrostatic grouting to hydrodynamic grouting, from aboveground to underground, geophysical and geochemical prospecting technologies are being widely applied to detect water hazards and identify water sources.

(3) Pore water above coal seam and other major water hazards are to be the focuses of research on inrush mechanism and R&D on comprehensive technologies in water control. Qualitative and quantitative identification of the multiple hazards in one water inrush will be the breakthrough in the technological advancement for coalmine water control.

Acknowledgement

This article is funded by National Natural Science Foundation of China (41373095) ，Anhui Science and Technology Breakthrough Project (1501zc04048) and Suzhou Regional Development Coordination and Innovation Center Fund (Research Direction on the Prevention and Treatment of mine water hazards，2013szxtcx001).

References

[1] T.J. Fan. A comprehensive guidebook to water control in coalmines. Jilin Audio-Visual Press, 2003, pp. 3-31.
[2] Q. Wu, S.Q. Zhao, S.N. Dong et al. Handbook to coalmine water control. China Coal Industry Publishing Home, 2013, pp. 28-40.
[3] Compilation Committee of Coalmine Water Control Experiences in China. A compilation of coalmine water control experiences in china. China Coal Industry Publishing Home, 1998, pp. 1-11.
[4] H.R. Gui, Y.B. Hu. Calculation methods of stress analysis for reasonable retainment of water-resisting coal (rock) pillars. China Coal Industry Publishing Home, 1997, pp. 50-60.
[5] Z.H. Ge, W. Shen, H. Bei. Preliminary research in the hydrogeology of water bursting of upper mining shaft on Ordovician limestone aquifer in a certain mine of Xuzhou, Jiangsu. Jiangsu Geology, vol. 18, no. 2, pp. 91-96, 1994.
[6] Beijing Mining Research Institute of China Coal Research Institute. Patterns of surface movement and overlying strata deformation in coalmines and applications. China Coal Industry Publishing Home, 1981, pp. 55-65.
[7] H.R. Gui, L.W. Chen, X.M. Song. Research on water and sand control for coalmining in the shallow part of areas covered by thick loose-bed.

China University of Mining and Technology Press, 2015, pp. 8-12.
[8] Ministry of Coal Industry. Coalmine hydrogeology protocol. Ministry of Coal Industry, 1984.
[9] Ministry of Coal Industry. Protocols for coal pillar retainment in major roadways and compressed coal mining under buildings, water bodies, and railways. China Coal Industry Publishing Home, 1985.
[10] Ministry of Coal Industry. Protocols on coalmine water control. China Coal Industry Publishing Home, 1986.
[11] X. H. Wang. The multi-parameters measuring method forecasting water inrush from working-faces. Coal Geology & Exploration, vol. 26, no. Supplement, pp. 36-39, 1998.
[12] B.Y. Li, G.H. Shen, Z.G. Jing. Theory and practice to prevent water inrush in floor coal seam in mining panels. In: Conference Proceeding of the 22nd International Conference of Mining Safety. China Coal Industry Publishing Home, 1987, pp. 65-70.
[13] State Administration of Coal Mine Safety. Regulations on coalmine water control. China Coal Industry Publishing Home, 2009, pp. 91-92.
[14] H.R. Gui, B. K. Sun. Study meaning and the core content of the control theory about water inrush from bed bottom in deep mining. Journal of Huainan Institute of Technology, vol. 19, no. 3, pp. 1-4, 1999.
[15] H.R. Gui, N.Q. Gong, B.K. Sun. Study of control theory on water inrush from bed bottom in deep mining - basic study thinking and plan.Journal of Huainan Institute of Technology, vol. 19, no. 4, pp. 1-4, 1999.
[16] H.R. Gui, E.Q. Yao, X.M. Song. Research on recycling technology of coalmine water. China University of Mining and Technology Press, 2011, pp. 3-12.
[17] H.Q. Shi. Applicaiton of measurement while directional drilling technology in preventing and controlling the water disasters in coal mines. Modern Mining, no. 4, pp. 38-41, 2014.
[18] J. Fang, J. Lu, Y.Z. Zhang, et al. Technology and application of precise detection and drainage of goaf water by directional long borehole. Coal Geology & Exploration, vol. 43, no. 2, pp. 101-105, 2015.
[19] H.R. Gui, L.W. Chen. Hydrogeochemistric evolution and discrimination of groundwater in mining district. Geological Publishing House, 2007, pp. 13-16.
[20] S.R. Barth. Stable isotope geochemistry of sediment-hosted groundwater from a Late Paleozoic-Early Mesozoic section in central Europe. Journal of Hydrology, vol. 235, pp. 80-86, 2000.
[21] W.Z. Gu, Z.H. Pang, Q.J. Wang, et al. Isotope Hydrology. Science Press, 2011, pp. 551-572.
[22] H.R. Gui, L.H. Sun, L.W. Chen, et al. Rare earth element geochemistry of groundwater from a deep seated sandstone aquifer, northern Anhui province, China. Mining Science and Technology, vol. 21, no. 4, pp. 477-482, 2011.
[23] L.W. Chen, X.X. Yin, H.R. Gui, et al. Water-rock interaction tracing and analysis of deep quifers in the mining area using isotope and hydrochemistry methods. Acta Geologica Sinica, vol. 87, no. 7, pp. 1021-1030, 2013.
[24] L.H. SUN. Heavy metals in groundwater from deep seated aquifer in northern Anhui Province, China: source identification and quantification. Fresenius Environmental Bulletin, vol. 24, no. 10, pp. 3467-3472, 2015.
[25] S. Chen. Comparative study of differing statistical methods in groundwater source identification: A case study. International Journal of Earth Sciences and Engineering, vol. 8, no. 2, pp. 597-603, 2015.