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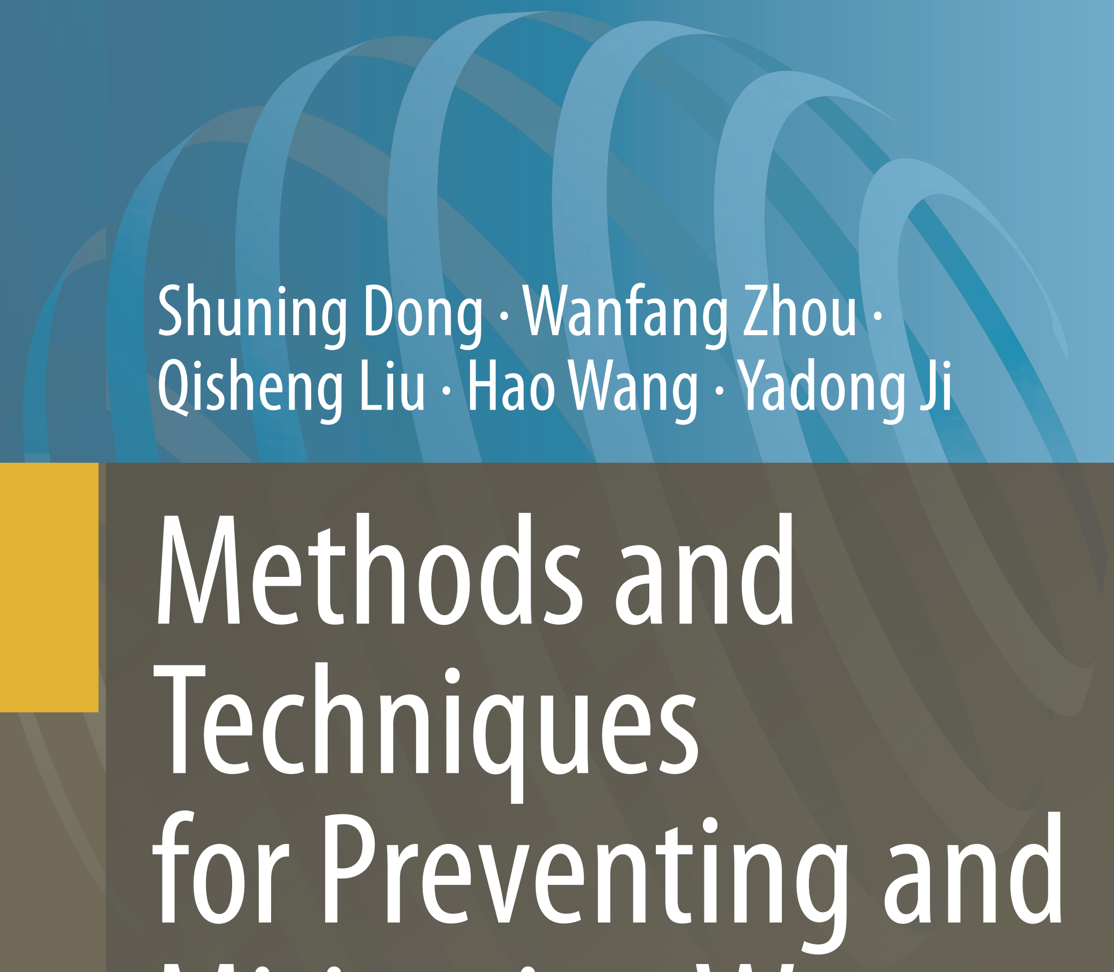

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Methods and Techniques for Preventing and Mitigating Water Hazards in Mines

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Preface

Mine water inflows have a variety of origins. Access shafts or open pits often intercept aquifers before reaching the mining horizons. These aquifers may be shallow phreatic or deeper confined, and their nature may range from porous alluvial deposits or sandstones to intensely fractured and karstified limestones. Underground tunnels, galleries, and working faces may encounter faults or karst collapse columns that can transmit groundwater through relatively impermeable zones from aquifers into mine workings. Similarly, the presence of faults and other discontinuities in the rock mass may present water problems for developments under bodies of water such as lakes, reservoirs, rivers, and the sea, or to developments in close proximity to abandoned mine pools, unsealed or poorly sealed shafts and boreholes. To these pre-existing water pathways must be added the induced or modified water pathways due to mine development and mineral extraction. Hydraulically conductive channels may be created by mining through roof or floor strata to connect with the sources of water. Water hazards in the form of water inrush often occur during mining and account for many of mine disasters and casualties in many countries of the world. According to statistics by Chinese State Administration of Production Safety Supervision and Management, the water inrush disasters are second only to the gas explosion disasters in coal mines in the serious and extraordinarily serious accident categories. Mine water inrushes not only cause casualties, but also are the most serious of mine accidents in terms of economic losses, accident emergency rescue, and mine restoration effort.

Major accomplishments have been made in predicting, preventing, detecting, and mitigating the water hazards in mines during the last three decades. Practices have demonstrated that conceptual site models that describe the mine water inflow pathways from water sources to working areas are essential to address both the safety issues and environmental impacts posed by mining activities. The traditional dewatering method must be carefully evaluated during environmental impact studies to comply with the current regulatory policy of green and water-conservation mining. Sophisticated multi-porosity and multi-permeability numerical models are available to predict mine water inflows more accurately. Advanced geophysical techniques and early warning monitoring devices are being implemented to detect and capture anomalies that are indicative of water inrushes. Water inrush risk assessment is supplemented with new methods including the vulnerability index approach that addresses the multi-factor, nonlinear, and mathematically non-amenable water inrush processes. Development of directional drilling technique makes it possible to implement targeted grouting proactively in specific stratum on a regional scale or to seal off localized water pathways in response to water inrush incidents.

This book presents the research results and practices of the above-mentioned topics in ten chapters. Chapter 1 gives the definition of water inrush in mines and provides an overview of the hazards associated with water inrushes. Chapter 2 presents the water inrush mechanisms and methods to evaluate water inrush risks. Chapter 3 describes various methods in predicting water inflow into mines from heterogeneous karst aquifers. Chapters 4 through 7 document eleven case studies in which the state-of-the-art methods and technologies are applied to solving water hazard problems under different conditions. The case studies in Chaps. 4 and 5 deal with water hazards posed from aquifers underlying and overlying coal seams, respectively. The case study in Chap. 6 deals with water hazards posed from an abandoned mine pool, whereas the case study in Chap. 7 discusses water hazards associated with a surface river in a quarry. Chapters 8 and 9 describe environmental impact assessments for an underground mine and an open pit quarry, respectively. Both cases emphasize the importance of determining the water sources and pathways. Chapter 10 provides the best management practices in mine water prevention and control.

The greatest part of this practical reference book is the technology applications in the case studies. The book would not be complete without support of those who participated in these projects. We are in debt to all of them. We would like to thank Xi'an Research Institute of China Coal Technology & Engineering Group Corp for providing most of the case studies and drafting most of the graphics. In particular, the following professionals are acknowledged for their significant contributions to the projects: Jin Dewu, Huang Xuanming, Cheng Jiayuan, Wang Xinwen, Li Yunchao, Nan Shenghui, Zheng Shitian, Zhu Mingcheng, Ji Zhongkui, Wang Shidong, Cao Haidong, Li Gongyu, Liu Yingfeng, Liu Yang, Zhao Baofeng, Xu Feng, Wang Qiangmin, and Zhou Zhenfang. We would also like to express our gratitude to Drs. James W. LaMoreaux, Annet Buettner, and Prasanna Kumar Narayanasamy of Springer Nature for their support and encouragement in preparation of the book.

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Chapter 1
Water Hazards in Coal Mines and Their Classifications

1.1 Introduction

Mine water hazards are often caused by mine water inrushes. Mine water inrush is a phenomenon in which a large volume of water unexpectedly gushes into underground workings or open pit mines when tunneling or mining exposes water-bearing media, such as high-pressure confined aquifers, surface water bodies, or underground mine pools. Mine water inrush generally occurs dramatically and can flood underground workings in a short period of time, jeopardizing mine production and causing casualties (Gui et al. 2017; Zhang et al. 2017; LaMoreaux et al. 2014). China is currently the largest coal producing country in the world; its coal resources encompass a large geographical area with various environments (Sun et al. 2015). Furthermore, China consists of multiple tectonic plates that were spliced through numerous tectonic movements, resulting in complex hydrogeological conditions in many coal mines (Yin et al. 2018; Zhao et al. 2017). Therefore, China is one of the countries in which coal mining is most seriously impacted by mine water inrushes (Yang et al. 2017; Lu et al. 2017; Yin et al. 2018).

Statistics on serious and major coal mine accidents by China's State Administration of Work Safety (Sun et al. 2015; Wang and Meng 2018) indicate that mine water inrush is the second most serious disaster type after gas explosions. More than 2.5 × 1010 tons of coal reserves are currently threatened with water inrush, mainly in developed industrial areas including north China, east China, and south China where coal reserves account for approximately 70% of the national coal resource. In the last 18 years between 2000 and 2017, the water-related hazards and casualties in coal mines of China have been greatly reduced (LaMoreaux et al. 2014; Wei et al. 2016; Qiao et al. 2017; Wang et al. 2017; Wu et al. 2017; Zhang et al. 2017; Xu et al. 2018). The improvement is primarily attributed to three factors: (1) progress of science and technology in mine water control and management, (2) updated mining equipment and mining technology, and (3) implementation of more stringent regulations on mine safety.

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Although the number of accidents and casualties has declined, the casualties and property losses induced by these accidents are still concerns. It is imperative to recognize the current situation of mine water inrush, study countermeasures for preventing water inrush and take effective engineering controls (Zhang et al. 2014, 2018a, b; Yang et al. 2017). Mine water inrush disaster control and water resource utilization will still be one of the important research topics to achieve accident-free and scientific mining in China (Zhang 2005; Qiu et al. 2017; Li et al. 2018).

1.2 Water Inrush Conceptual Site Models for Coal Mines of China

Development of conceptual site models (CSMs) will provide necessary guidance for further improving the safety records in coal mining. A CSM is a description of relationships between sources and receptors under both natural and man-made environments based on existing knowledge (Zhou and Lei 2017). It describes sources of water recharging the mine as well as complete, potentially complete, or incomplete exposure pathways from the sources to the mining area. The CSM serves as a planning tool, a modeling and data interpretation aid, and a device that assists the project team in communicating with the public, integrating information and making informed decisions. These decisions can range from water inrush risk assessment to engineering measures for risk reduction. A well-thought CSM also provides a structure to summarize and display information about a site and identify additional information needed to develop technically sound decisions. Table 1.1 presents a general CSM for coal mines of China. The CSMs include the ecological environment as another essential receptor in evaluating engineering measures for mine water control.

1.2.1 Development of Water Inrush Conceptual Site Models

The CSM includes three types of water sources: surface water, water in underground mine pools, and groundwater. Each type of water source is divided into different categories based on their origins. The threats posed by water inrushes consist of direct threats and indirect threats, and for the purposes of this document are differentiated by the terms hazard and risk. Water inrush presents a hazard of direct physical injury to miners and damage to working spaces in tunnels and working panels. Water inrush also presents a risk to the environment through indirect exposures. Surface subsidence, water resource reduction and contamination, and adverse impacts on biodiversity are examples of these indirect consequences of water inrushes. Both hazards and risks must be considered in water inrush assessment. The degree of hazard and risk posed by water inrush is usually proportional to the strength of water

Table 1.1 Water inrush CSMs for coal mines of China

		Water Inrushes						Applicability to Regions of China (Figure 1.1)
		Hazard or Direct Injury			Risk to Ecological Environment			
Water Sources	**Pathways**	**Worker Safety & Health**	**Flooding of Tunnel**	**Flooding of Working Panel**	**Surface Subsidence**	**Water Resource**	**Crops and Biodiversity**	
Surface water: Precipitation Runoff	Shaft	●	○	○	◎	●	◎	1-6
	Mining-induced fracture	●	○	○	◎	●	◎	
	Sinkhole	●	○	○	◎	●	◎	
	Poorly sealed borehole	●	○	○	◎	●	◎	
Surface water: River/Lake/Reservoir	Shaft	○	○	○	◎	●	◎	
	Mining-induced fracture	●	○	○	◎	●	◎	
	Sinkhole	○	○	○	◎	●	◎	
	Poorly sealed borehole	●	○	○	◎	●	◎	
Surface water: Mining-induced Subsidence Pond	Shaft	●	○	○	◎	●	◎	
	Mining-induced fracture	●	○	○	◎	●	◎	
	Sinkhole	●	○	○	◎	●	◎	
	Poorly sealed borehole	●	○	○	◎	●	◎	
Water in abandoned mines: Accumulated water in old mining area of same mine	Direct exposure by tunneling	●	○	○	◎	●	◎	1-6
	Mining-induced fracture	●	○	○	◎	●	◎	
	Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
Water in abandoned mines: Accumulated water in neighboring mine	Direct exposure by tunneling	●	○	○	◎	●	◎	
	Mining-induced fracture	●	○	○	◎	●	◎	
	Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	

(continued)

Table 1.1 (continued)

			Water Inrushes						Applicability to Regions of China (Figure 1.1)
			Hazard or Direct Injury			Risk to Ecological Environment			
Water Sources		Pathways	Worker Safety & Health	Flooding of Tunnel	Flooding of Working Panel	Surface Subsidence	Water Resource	Crops and Biodiversity	
Groundwater: Groundwater directly intercepted by mining activities	Fractured sandstone aquifer	Direct exposure by tunnel	●	○	○	◎	●	◎	1–6
		Direct exposure by mining panel	●	○	○	◎	●	◎	
	Thin-bedded limestone aquifer	Direct exposure by tunnel	●	○	○	◎	●	◎	
		Direct exposure by mining panel	●	○	○	◎	●	◎	
Groundwater: Groundwater overlying working area while separated by an aquitard under natural conditions	Porous medium aquifer	Mining-induced fracture in overlying formation	●	○	○	◎	●	◎	1–6
		Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
		Hydraulically conductive karst collapse column	○	○	○	◎	●	◎	
	Fractured sandstone aquifer	Mining-induced fracture in overlying formation	●	○	○	◎	●	◎	
		Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
		Hydraulically conductive karst collapse column	○	○	○	◎	●	◎	
	Thin-bedded limestone aquifer	Mining-induced fracture in overlying formation	●	○	○	◎	●	◎	
		Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
		Hydraulically conductive karst collapse column	○	○	○	◎	●	◎	

(continued)

Table 1.1 (continued)

			Water Inrushes						**Applicability to Regions of China (Figure 1.1)**
			Hazard or Direct Injury			**Risk to Ecological Environment**			
Water Sources		**Pathways**	**Worker Safety & Health**	**Flooding of Tunnel**	**Flooding of Working Panel**	**Surface Subsidence**	**Water Resource**	**Crops and Biodiversity**	
Groundwater: Groundwater underlying working areas while separated by an aquitard under natural conditions	Thin-bedded limestone aquifer	Mining-induced fracture in underlying formation	●	○	○	◎	●	◎	1–3
		Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
		Hydraulically conductive karst collapse column	○	○	○	◎	●	◎	
	Thick-bedded limestone aquifer	Mining-induced fracture in underlying formation	●	○	○	◎	●	◎	
		Hydraulically conductive fault/fracture	●	○	○	◎	●	◎	
		Hydraulically conductive karst collapse column	●	○	○	◎	●	◎	

sources, the pumping capacity of the mine, and the ecological sensitivity to water regime changes. The CSM also describes the pathways from each source to various receptors. Direct exposure to water-bearing formations, mining-induced fractures in overlying or underlying aquitards, hydraulically conductive faults and karst collapse columns, and poorly sealed boreholes are potential pathways, making water inrush possible (Zhou and Li 2001; Tan et al. 2010; Yin et al. 2018).

CSM development is an iterative process that reflects the progressive understanding of a study site from initial hydrogeological investigation to water control during coal mining. Potential sources of water and receptors should be documented in the initial CSM. Complete or potentially complete exposure pathways are focuses on hydrogeological investigation and data collection. For example, analysis of the groundwater pathway will usually entail some hypotheses on groundwater flow velocity or direction relative to potential receptors. If these parameters are not known, they can be measured through hydrogeological investigation or interpreted through modeling or professional judgment. If the results from data collection confirm the interpretations, the CSM is updated to show that the hypothesis is correct. However, if results do not support the predicted outcome, the hypothesis should be restated, leading to a revision to the existing CSM.

Geographically, China can be divided into six regions (Fig. 1.1). Applicability of the CSM to different regions is presented in Table 1.1 as well. Surface water and

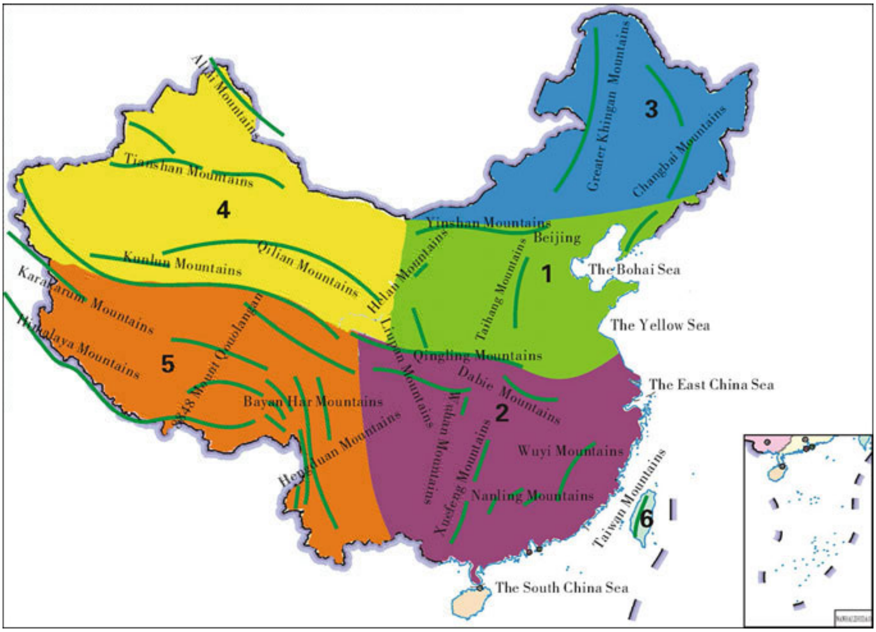

Fig. 1.1 CSM-based water inrush regions in China

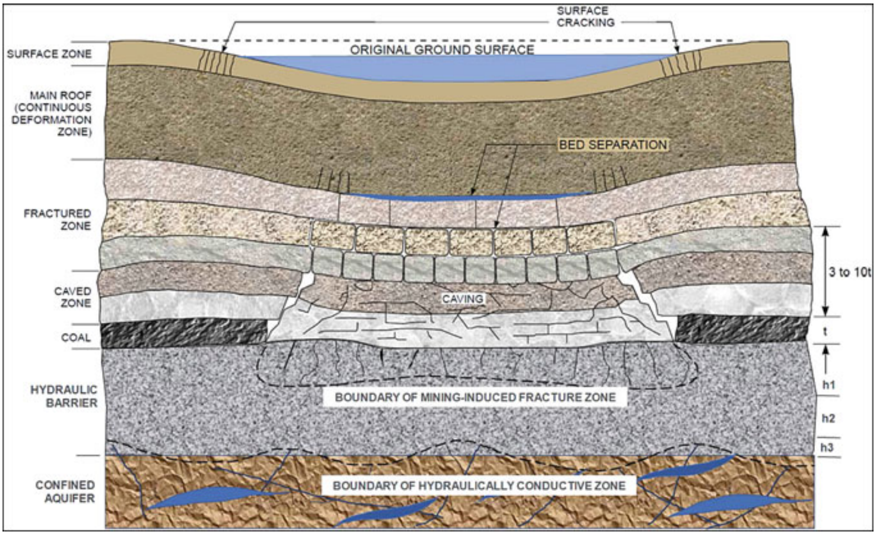

Fig. 1.2 CSM showing water threats from water bodies both underlying and overlying the coal seam (t—coal seam thickness; h1—height of mining-induced fracture zone in the top of aquitard immediately underlying the coal seam; h2—thickness of intact aquitard; h3—height of hydraulically conductive zone in the bottom of aquitard)

water in underground mine pools occur in all the regions, whereas water inrushes from aquifers both overlying and underlying coal seams occur only in Regions 1 through 3.

The water inrush CSM can also be shown in diagrams to illustrate the pathways from water sources to receptors. Figure 1.2 shows a CSM for water inrush threats from both the underlying and overlying aquifers. Various factors that may affect occurrence of water inrushes are displayed in the CSM. Natural water-conductive faults or fractures as well as mining-induced fractures can be parts of complete pathways for water bodies either overlying or underlying the coal seam (Tan et al. 2013; Li et al. 2015; Wang et al. 2017).

1.2.2 Benefits of Water Inrush Conceptual Site Models

Water inrushes in coal mines of China pose threats to workers' safety, mine property, and the ecological environment. Representative water inrush CSMs provide an innovative tool to better understand water inrush mechanisms, help with pathway analysis in water inrush risk assessment and identify data gaps for further investigations, promote integration of water hazard control and ecological environment risk reduction. They also drive proactive engineering measures for water inrush prevention and mine water control to eliminate or reduce water inrush hazards and ecological deterioration risks. Therefore, the authors recommend that a CSM be developed for each mine and each mining area and updated on a regular basis. Development of water inrush CSMs for coal mines of China can serve the following purposes:

- Provide an innovative tool to better understand the water inrush mechanism, and design large-scale analog simulation models. With the increase in both mining depth and mining scale, additional problems may be caused by high stress, high temperature, high water pressure and high gas pressure. The water inrush mechanisms can be complex with diversified characteristics. Delayed water inrush or mining-induced bed separation water inrush in the shallow zone occurs more frequently. The CSM approach will help identify the complete, potentially complete, and incomplete pathways for either mathematical simulations or physical analog models.
- Help with pathway analysis in water inrush risk assessment and identify data gaps for further hydrogeological investigations. Water inrush risks are typically performed for complete pathways, whereas water inrush probability is provided for potentially complete pathways. Potential complete pathways between sources and receptors are often the data gaps, which form the basis for additional data collection efforts. New data on sources, interactions and receptors are compared to the current CSM to refine it as necessary. This in turn may result in additional data gaps that may impact the design of site characterization. The CSM may also help identify modeling that may be required to determine whether there is an unacceptable risk to receptors.
- Promote both hazard control of water and risk reduction of the ecological environment. The early Middle Jurassic coal fields in the northwest and western side of north China are in arid and semi-arid environments where the annual precipitation ranges from 250 to 450 mm. The natural ecological environment is fragile and sensitive to any changes of the water table. The CSMs call for a strategy that will conserve the water resource and protect the ecological system while keeping the water under control for a safe working environment in the mines. In east China, mining is severely threatened by the confined karst water from the Ordovician limestone and water in underground mine pools. Representative CSMs in this area can help resolve conflicting issues concerning coal mining safety, water resource management, and ecological protection and lay a foundation to achieve not only safe mining but also green mining.
- Drive proactive engineering measures for water inrush prevention and mine water control to eliminate or reduce water inrush hazards and ecological deterioration risks. Any engineering measures will be targeted to either water source removal or pathway elimination or both in the CSMs. Water inrush risks are often high in north China's coalfields where the aquitard or hydraulic barrier between the lower group coal seams and the underlying confined aquifer is relatively small. Large-scale grouting operations to reinforce the hydraulic barrier are considered to be effective engineering measures to eliminate the pathways. Grouting reinforcement technology injects a large quantity of grout directly into the targeted formation

according to rational design. Thin-bedded aquifers can also be the targeted formation for grouting, depending on their spatial relationship with the coal seams. The grout will fill the karst-fissures and cracks of the aquifer, transforming the aquifer into a hydraulic barrier.

1.3 Classification of Water Inrush for Coal Mines of China

1.3.1 Principles for Classification of Mine Water Inrush

Mine water inrush studies suggest that different types of water inrush generally call for different prevention and control technologies. Therefore, it is necessary to classify water inrushes according to their distinct characteristics. Due to diversity and complexity of mine water inrush, the systematic, consensus and comprehensive classifications of mine water inrush are rarely reported at present. In fact, scientific classification of mine water inrush is a huge systematic classification project and needs to develop qualitative, quantitative, and combined classification methods. Furthermore, it requires a large amount of field data and cases of water inrush as well as supports of relevant scientific theories. Therefore, the classification of mine water inrush has important theoretical and practical value for basic theory research, investigation and exploration, evaluation and prediction, design of detection equipment, prevention and control technologies, and comprehensive utilization of mine water.

The division bases need to be established prior to classification of mine water inrush. According to case histories of water inrush and specific characteristics, water recharge source, water flow channel, water recharge strength, harm forms, economic loss and casualties, and time-varying characteristics are used as the bases for classifying water inrush. Water recharge source refers to all of the water sources that exist in and show hydraulic connections with ore bodies and surrounding rock strata that can cause continuous mine water inrush during the mining process. Water recharge channel is the path for these water sources entering into mines. Harm forms indicate pit water inrush showing characteristics, such as abnormal temperature and corrosivity. In addition, economic losses and casualties measure the magnitude of economic losses and the number of casualties directly resulting from mine water inrush, respectively. Time-varying characteristics show the temporal relationship between mine water inrush and the progress of mining engineering.

1.3.2 Types of Mine Water Inrush

Classifying mine water inrush in accordance with water recharge source. Based on the nature of water recharge source, water inrush can be divided into water inrush of natural and artificial sources (Fig. 1.3). The natural water recharge source includes the mine water inrush directly recharged by atmospheric precipitation, mine water

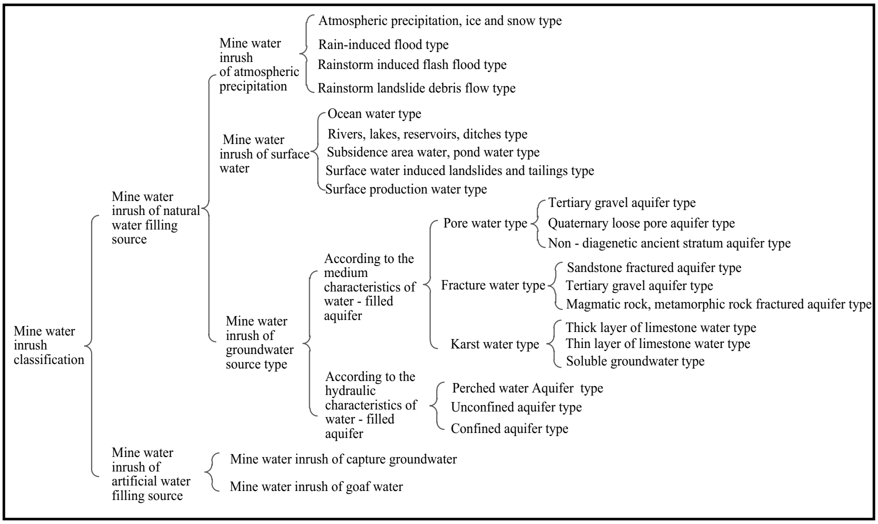

Fig. 1.3 Classification of water inrush based on recharge sources

inrush of surface water recharge sources (large-scale surface water bodies, such as seas, lakes, rivers, pools, bogs and reservoirs) and water inrush of groundwater source. Among them, the groundwater source type water inrush can be divided into unconsolidated pore water recharge source type, bedrock fissure water recharge source type and karst water recharge source type in soluble karst rocks through medium characteristics of water recharge aquifers. According to hydraulic characteristics of water recharge aquifers, the groundwater source type water inrush can be divided into perched water source type, phreatic water recharge source type and confined water recharge source type. In addition, the artificial source water inrush consists of mine water disasters of groundwater captured source type and goaf water source type.

The classification can also be carried out according to the location and contact relationship between minable seams and water recharge aquifers. In accordance with the relative locations of minable seams and water recharge aquifers, water inrush can be classified water inrush from coal roof, coal floor and periphery water recharge source. Furthermore, based on the contact relationship between minable seams and water recharge strata, water inrush can be further divided into six types with direct and indirect roof water recharge source, direct and indirect floor water recharge source, and direct and indirect surrounding water recharge source.

Water disasters can also be classified in light of the water recharge channel. Water recharge channel can be divided into natural and artificial water recharge source passages. The natural water recharge source passages include water inrush with point karst collapse column passage, linear fracture (fissure) zone passage, narrow strip concealed outcrop passage, plain fracture network (thinning area of partial plain aquifuge) and earthquake-induced passage. The artificial water recharge source passages are divided into those with passages in roof caving fractured zone, roof cut caving fractured zone and roof pump caving zone, floor rock pressure failure zone, floor draft zone of confined water, ground karst collapse zone and poorly-sealed boreholes.

Mine water inrush can be classified according to the harm forms into normal temperature, moderate to high temperature or corrosive water disasters. One can divide mine water inrush in accordance with economic losses and causalities. In accordance with causalities or direct economic losses, mine water disasters can be divided into extremely large, very large, large, and minor ones. Classification can be carried out according to time-varying characteristics as well. Based on time-varying characteristics, water inrush is divided into instant, hysteresis, or gradually varying ones.

1.3.3 Characteristics of Mine Water Inrushes

Mine water inrush directly recharged by atmospheric precipitation: Atmospheric precipitation is the main supply source of groundwater, and all ore deposits filled with water are directly or indirectly related to atmospheric precipitation. The source of atmospheric precipitation described here indicates the only water source for direct water recharge of ore deposits. There is a synchronous correlation or delayed correlation between the disaster time and the precipitation time. Moreover, catastrophic risk is related to precipitation and rainfalls and is generally proportional to rainfalls.

Water inrush of surface water: For ore deposits close to large-scale surface water bodies, such as seas, lakes, rivers, reservoirs and pools, it is critical to clarify the influences of surface water under natural conditions and after mining on ore deposit mining. This is a key process of hydrogeological exploration in mining areas and hydrogeological work in mines. Surface water is generally large in volumes. Once surface water forms hydraulic connection with mining activities and influencing ranges, the catastrophic risk is likely to rise.

Water inrush of groundwater: This type of disasters is complex. According to medium characteristics of water recharge aquifers, the water inrush can be divided into those with sources of pore water recharge unconsolidated sediments, bedrock fissure water recharge and karstic water recharge in soluble rocks. Furthermore, perched water, phreatic water and confined aquifer source water disasters are included in this type in accordance with hydraulic characteristics of water recharge aquifers. From the perspectives of water-bearing media and hydraulic characteristics, confined aquifers of karstic water show strong water abundance in general. Therefore, once such aquifers are connected due to mining activities and influencing ranges, the water inrush of karstic water source generally demonstrates the greatest catastrophic risk.

Water inrush of captured water: Because of mining, the groundwater cone of depression constantly extends, and thereby mining activities strongly transform natural groundwater flow fields in mining areas. The new supply water source obtained in artificial groundwater flow fields is known as captured water source. The captured water source includes spring water in groundwater drainage areas, surface water (seas, lakes, and rivers), the neighboring aquifers in one side of drainage areas in groundwater flow zone in mining areas and groundwater in the adjacent hydrogeological units. Therefore, the catastrophic risk is generally proportional to water abundance of the supply source.

Water inrush of goaf water: Because part of goaf remained open after mining, the goaf becomes filled with water in the late stage, becoming mine pools. If the edge of water bodies is mined, water in the goaf can suddenly gush into underground mines, causing mine water inrush accidents. According to statistics, this type of inrush has the largest number and strongest catastrophic risk in serious mine water disasters. Such a type of mine water inrush is unexpected with large amounts of water inflow, causing great damages. The goaf water is often acid and shows high concentration of hydrogen sulfide gas. However, due to the limited size of the water-storing space, the water flow may last for a short duration, and the water can be easily drained.

Mine water inrush of roof water: Mine water inrush of roof source occurs when mining activities and influencing ranges (caving and fissured zone and water-flowing structure) affect the aquifers overlying the ore body. The catastrophic risk is directly related to the water abundance and connectivity of the overlying water recharge aquifers. Greater catastrophic risk results from stronger water abundance and connectivity of aquifers in the influencing ranges of mining activities.

Mine water inrush of floor water: Mine water inrush of floor source is triggered when the mining activities and influencing ranges (zone destroyed by mine pressure and water-flowing structures) affect aquifers underlying the ore body. Similar to the water inrush of roof source, the catastrophic risk of floor water inrush is directly correlated with water abundance in and connectivity to the underlying aquifers. If aquifers in the influencing ranges of mining activities show remarkable water abundance and connectivity, the catastrophic risk of mine inrush is strong.

Mine water inrush of periphery water: Such disasters result from mining activities and influencing ranges affecting the aquifers around the ore bodies. The water recharge sources can be direct or indirect. The catastrophic risk has a proportional relation with water abundance of surrounding water recharge aquifers and connectivity of fissures. In general, direct water recharge sources in above three types of mine water inrush refer to the water source directly contacted with mined ore or water source which can be affected by roof water flowing caving zone or floor rock pressure failure zone and thereby contacted with mined ore bodies. The indirect water recharge source indicates the water recharge source that enters mines by passing through water-resisting rocks through certain water flowing structures or via leakage. It mainly distributes around mined ore body but does not directly contact with ore bodies or locates outside normal caving zone or zone destroyed by mine pressure.

Mine water inrush through natural water recharge passage: While mining ore bodies, various paths for water recharge source entering pits are referred to as water-flowing passages. Moreover, the mine water disaster caused by water gushing into pits through non-artificial water-flowing passages is called water inrush of natural water flowing passage. The characteristics are described as follows:

- In case of water inrush through karst collapse column passages, the groundwater in coal series strata and different water recharge aquifers can be hydraulically connected by karst collapse column passages, thus increasing catastrophic risk of such mine water disasters.
- Water inrush through passages in linear fracture (fissure concentrated) zone mainly takes place in fault concentrated zone, fault intersection point, fault convergence or fault tip. The passages link the close hydraulic connection between water recharge rock strata, thus causing mine water disasters.
- In view of water inrush of narrow strip concealed outcrop passage, according to the practical experience in China, the Quaternary pore aquifer group is very likely hydraulically connected to the coal series and water-recharge aquifer group of the thick carbonate formations at the narrow strip concealed outcrops. As a result, water disaster happens through narrow strip concealed outcrop passages, resulting in high catastrophic risk.
- Water inrush through passage in plain fracture networks (thinning area of local plain aquifuge). In the northern area of north China type coalfield, stresses have been released through rock fracturing in the brittle water-resisting strata under multi-stage tectonic stresses in the geological history. Therefore, concentrated cracks and joints in different directions are present in the water-resisting strata. These fractures and joints form plain extended fracture networks with a planar distribution. With the increases of groundwater head difference in the upper and lower water recharge aquifer groups, such fracture networks form vertical water exchange in a plain leaky form and cause water disasters of plain fracture network passages.
- Water inrush through earthquake-induced passage. When strong earthquakes occurred, fractures in different scales were formed near the epicenter by coupling of cyclic tension and compression of seismic forces with shear. Mine water inrush disaster occurs when fractures near the coal seams develop and connect with surrounding aquifers.

Mine water inrush through artificial water flowing passages: The mine water inrush caused by water gushing into mines through artificial water flowing passages is known as inrush of artificial water flowing passage. Such type includes water inrush with passages in the following media:

- Roof caved-in zone
- Roof fractured zone
- Roof caved-in collapse zone
- Zone destroyed by mine pressure of floor
- Floor penetration zone by confined water

- Ground karst collapse
- Poorly sealed borehole.

The first three sub-types are similar and caused by the fact that upper aquifers are connected due to roof rock damages trigged by mining activities. The difference is that caved-in zone is mainly developed in horizontal or gently tilted strata, while caved-in collapse zone is mainly developed in steep dip strata. Furthermore, water-conductive fracture zone forms in thick and extremely thick strata of sandstone or coarse sandstone with a large modulus of elasticity on the roof of coal seams. Caving does not happen in limited mining ranges. When caving occurs, it takes place in a large range, damaging roofs, or floors. Similarly, sub-types for floor strata are similar. They lead to mine water disasters because the lower aquifers are connected to the mining area as a result rock damages induced by mining activities. The differences lie in that zone damaged by mine pressure in zone destroyed by mine pressure of floor is formed in strata closely neighboring the lower ore bodies, while draft zone of confined groundwater in floor penetration zone develops in the top of lower aquifers of ore bodies. Large-scale water pumping and dewatering practices of karst water-recharge deposits, surface karst collapse is well developed in mining areas and surrounding areas. These collapses allow surface water and atmospheric precipitation to be filled into mines. When roadways or working face is advanced to intercept poorly sealed boreholes, groundwater in roof and floor water recharge aquifers of coal seams gush into tunneling face via these boreholes.

Normal temperature, moderate to high temperature and corrosive water inrush: The normal temperature water disaster refers to water inrush in the normal temperature range of local groundwater. Under the effects of abnormal geothermal, the water disaster in which the temperature of water inrush is higher than the normal water temperature is known as moderate to high temperature water disaster. Corrosive water disaster means that the source of water inrush is corrosive to mining machinery equipment, drainage equipment and roadways.

Instant, hysteresis, skipping and gradually varied water inrush: Instant water disaster refers to the water inrush occurring in the working face of mines while hysteretic water disaster refers to that appearing in the goaf behind the working face. With the gradual growth of mining depth and large-scale mining of deep coal seams, the crustal stress and water pressure of the mining environment also increase. Hysteresis water disasters induced by different passages including faults, fracture concentrated zones or karst collapse columns occur more frequently in recent years. Skipping water disaster refers to water inrush during which the inrush amount constantly changes with time while gradually varied water disaster is water inrushes during which the inrush amount gradually increases or decreases.

1.4 Hydrogeological Classification for Mine Water Hazard Control

1.4.1 Criteria of Hydrogeological Classification

Methods and techniques for water control and management depend on the CSM of each mine. Based on their hydrogeological complexity, coal mines in China are divided into four classes: simple, moderately complex, complex, and extremely complex. The hydrogeological classification helps with design of the supplemental exploration, understanding of the mine hydrogeological condition, and the prevention and control of water inrush event (Wu 2014). Table 1.2 presents the hydrogeological classification criteria, which are based on the following factors:

- The degree to which the aquifers or water bodies are affected or destroyed by mining
- The distribution of old mine pooling within the mine and its vicinity
- The amount of water inflow
- The amount of water inrush
- The risk posed by water hazard
- The difficulty in water prevention and control.

The hydrogeological classification can be an iterative process. The classification system is updated as more data become available and better understanding of the mine conditions is obtained. The amount of water inflow is determined by the representative of the main aquifer in the mine. When there are more coal seams in the same mine field and the hydrogeological conditions vary greatly, the coal mines should be evaluated based on their hydrogeological complexity. The hydrogeological type of the mine is typically biased to the complex end if uncertainty in the data is present.

1.4.2 Hydrogeological Classification of Coal Mines in China

Based on the data collected by China's State Administration of Coal Mine Safety in 2012 (Sun et al. 2015), approximately 1% coal mines were extremely complex in hydrogeological conditions, 7% coal mines were complex, 36% coal mines were moderate complexity, and 56% coal mines were simple. Figure 1.4 shows the distribution of hydrogeological classifications for the surveyed coal mines. Approximately 70% of the hydrogeologically complex and extremely complex mines are in Shanxi, Heilongjiang, Anhui, Shandong, Henan, Hunan, Chongqing, Sichuan, and Guizhou provinces. Preventing and controlling water inrushes are extremely important in these mines.