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Prediction of water source and water volume of underground reservoir in coal mine under multiple aquifers

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ABSTRACT

The role of coal mine underground reservoirs (CMUR) in 'guide storage and use' greatly solves the problem of mine water waste. Replenishment and prediction of reservoir water sources provide an important support for the successful development of key technologies concerning CMUR. To study water replenishment for CMUR, the hydrogeological conditions of the Shendong mining area were investigated as an example. Based on the relationship between the development height of the 'two belts' of shallow coal seams and the relative occurrence of location of aquifers, the aquifers are generalized and classified according to occurrences location. Taking Bulianta coal mine as the research background, a discrete element fluid–solid coupling numerical simulation model is constructed to analyze the development characteristics of mining-induced fractures after coal seam mining, and the water replenishment channel of the CMUR is determined. On this basis, analysis is made on the change law of water pressure in the aquifer, aquifuge and coal seam roof under mining action. Taking hydraulic head pressure and water velocity as the judgment basis, prediction and evaluation are made on the water replenishment capacity of CMUR. The research results can provide references for coal mine safety production and mine water protection and utilization.

Key words: CMUR, hydraulic pressure, mining-induced fracture, reservoir replenishment source, water-rich aquifer

HIGHLIGHTS

- Based on the water-conducting fractured zone, the occurrence type of 'coal-water' is generalized.
- The change law of aquifer under different 'coal-water' conditions is revealed.
- The source and amount of water supply for CMUR were obtained under different conditions.

INTRODUCTION

In recent years, western China has become the 'main battlefield' for the development and utilization of coal resources and the improvement of industrial competitiveness, which provides a significant impetus for the rapid development of China's society and economy. The coal production and reserves in western China account for more than 70% of the country's total, while its water resources take up about only 3.9%, (Gu *et al.* 2016; Fan 2017; Chi *et al.* 2019a, 2019b), and the ecological environment is extremely fragile. The shortage of water resources has become a 'bottleneck' restricting the development of the coal industry. Traditional extensive mining and adoption of 'mining while controlling or controlling after mining' in ecological environments cause an 'ecological loss' far greater than the 'economic value' created by coal development. Coal mining in western mining areas can easily bring about natural disasters such as water loss, surface vegetation death, and land desertification, making the potential for natural environmental vulnerability turn into real destruction (Cao *et al.* 2019; Chi *et al.* 2021). The protection of ecological environments and water resources in mining areas has become a common problem faced by the industry. How to resolve the contradiction between coal mining and ecological environment has become a worldwide topic. According to statistics, China's annual output of mine water is about 5 billion tons, and only about 30% is utilized (Li *et al.* 2017, 2018). If fully utilized, it can not only provide a large amount of water for downstream coal processing, but also achieve the recycling of mine water. Therefore, the issue of 'mine water protection and utilization' has become a strategic requirement for the sustainable development of mining areas and an important prerequisite for the green development of coal resources (Cao *et al.* 2014).

At present, many scholars have carried out much theoretical research and engineering practice around 'water-preserved mining'. From the perspective of 'intercepting and drainage' (Wang *et al.* 2010; Fan 2017; Zhao *et al.* 2018; Zhang *et al.* 2019), much research has been done on mining-induced fractures and strata movement to master the development law of mining-induced fractures and coal mining effects on water resources. Through theoretical analysis and engineering practice, approaches are proposed, such as height-limited mining, mining with filling, ground water storage, etc., in an attempt to prevent mine water production or achieve ground storage, so that it is possible to avoid or reduce the mining damage to water resources (Wang *et al.* 2015), thus solving the problem of water resource destruction and ecological environment deterioration caused by coal mining (Gu & Zhang 2012). Previous research had focused mainly on mining-induced fractures and overlying strata activity law, etc. The purpose is to understand the impact of coal mining on water resources, so that corresponding measures can be taken to avoid or reduce damage (Wang *et al.* 2018, 2020a, 2020b, 2020c). However, this can be done only by analyzing the development of mining-induced fractures and overlying strata activity law, it is insufficient to understand the impact degree of mining on water resources. On this basis, if we can accurately and effectively grasp the change characteristics of aquifer water level under mining, it is possible to further clarify the relationship between coal resource mining and the destruction of underground aquifer water resources. Nevertheless, there are theoretical and technical problems. For instance, the currently proposed water-preserved mining methods and technologies have reduced mining efficiency and recovery rate to a certain extent, resulting in waste of resources; ground water storage faces such problems such as insufficient water storage space, high water storage costs, evaporation waste and serious water pollution. Moreover, it is difficult to grasp the link between fracture development and aquifer destruction (Yao *et al.* 2018; Liu *et al.* 2019; Wang *et al.* 2020b, 2020c). Therefore, mine water protection and utilization in mining areas in western China demand deeper analysis and exploration, and research should be conducted from the perspective of actual production and ecological water use in mining areas, thereby solving the contradiction between coal mining and water resources protection for water-scarce mining areas.

After more than 2 decades of scientific and technological research and engineering practice, Academician Gu Dazhao first proposed the concept and technical system of 'guide storage and use' for coal mine underground reservoirs (Gu 2015). At present, more than 30 underground reservoirs have been successfully constructed in Shendong mining area with a maximum water storage capacity of about 32 million m^3, contributing much to domestic water and industrial water in the mining area. Coal mine underground reservoirs make full use of the rock mass voids in the goaf to connect the safety coal pillars with artificial dams to form reservoir dams. At the same time, mine water inflow facilities and water intake facilities are built to make use of the natural purification effect of goaf rock mass on mine water. This technology breaks through the original concept of 'interception' for water preservation, and adopts the idea of 'guide storage and use' to divert mine water to the underground goaf for storage and utilization, thus avoiding evaporation loss, surface water treatment plant construction and high operating costs (Arefmanesh *et al.* 2009; Andrés *et al.* 2014; Flesch *et al.* 2018), which opens up a technical approach for the coordination between coal mining and water resources protection and utilization (Ma *et al.* 2015; Wang *et al.* 2019; Song *et al.* 2020; Zhang *et al.* 2020). After years of research and exploration, the academic community has carried out extensive theories and engineering practices around site selection of coal mine underground reservoirs, reservoir dam body design and stability, reservoir design, etc., gradually forming key technologies in water source prediction, reservoir site selection, and storage capacity designed to secure safe operation of the reservoir (Zhang *et al.* 2011; Gu 2015; Ju *et al.* 2017; Li *et al.* 2017, 2018; Liu *et al.* 2019; Yao *et al.* 2019).

Water source prediction is the basic prerequisite for the construction of coal mine underground reservoirs, which involves two aspects: the study of groundwater migration laws and water volume prediction. Water volume prediction provides the basis for a series of activities such as water pumping and injection in underground reservoirs (Gu 2015; Li *et al.* 2018). At present, water source prediction is mainly based on mine water inflow monitoring data. In fact, most underground reservoir water sources are derived from overlying aquifers of coal seams or bedrock fracture water, and reservoir water replenishment may come from a single aquifer or multiple aquifers. Aquifer replenishment capacity constitutes the core factor in reservoir's normal support of the production, life, and ecological water use in the mining area. The water source of the reservoir has a close relation to the disturbance characteristics of the aquifer and the development law of water flowing fracture. Therefore, determining the aquifer change law under the influence of mining constitutes the basis for studying water source of the reservoir. This paper carries out research exactly on this problem. With the underground reservoir of Bulianta coal mine in Shendong mining area as the background, it bases itself on the highly generalized aquifer occurrence model in development of water flowing fracture, conducts fluid–solid coupling numerical simulation and analysis with the help of UDEC discrete element simulation software, analyzes aquifer change law under the influence of mining, comparatively studies aquifer water pressure change of different models, and analyzes water source of the underground reservoir. The research results carry important academic value and practical guiding significance for accurately predicting water sources of coal mines in underground reservoirs (Figure 1).

GENERALIZED CLASSIFICATION OF 'COAL-WATER' OCCURRENCE RELATIONSHIP IN SHALLOW COAL SEAMS

After the coal seam mining, a goaf is formed, causing a series of activities such as breakage and migration of the overlying strata. As the working face continues to advance, the strata destruction continues to develop upward. When the coal seam mining affects the aquifer, water resources in the aquifer enters the goaf along the water flowing fracture, causing water resource waste. After years of research, the academic community believes that the main controlling factor that leads to loss of water resources in aquifers is the separating ability of the aquifuge. If mining-induced fracture destroys the separating ability of the aquifuge, it will cause excessive loss of water resources in the aquifer. For mining areas in western China, shallow burial depth and increase in thickness are the main characteristics of western mining areas. Coal mining inevitably destroys the separating ability of the aquifuge, making water resources from the aquifer flow into the goaf. To avoid this issue, many scholars have conducted much research on strata permeability after mining, development height of water flowing fracture, etc. by using on-site measurement, simulation analysis to analyze the disturbance characteristics of burial depth, mining thickness, mining speed and key strata position with regard to aquifers, and the corresponding calculation formula and judgment standard of fracture development height are proposed (Wang *et al.* 2018, 2020a, Chi *et al.* 2019a, 2019b; Zhang *et al.* 2019).

In fact, although mining-induced fractures communicate with aquifers, it does not necessarily become a water flowing fracture. Whether the fracture will become a water flowing fracture should be used as the judgment criterion for studying the influence of coal mining on aquifers. Therefore, the degree of aquifer damage under the influence of coal mining should be analyzed in view of the development height of the water flowing fractured zone, and the relationship between the water flowing fractured zone and aquifer occurrence location should be comprehensively considered. Based on the above analysis, the aquifer is generalized and classified to further confirm the source of water replenishment to the coal mine underground reservoir. The generalization principle is based on the relative position relationship between the aquifer occurrence location and development height of the water flowing fractured zone. The water flowing fractured zone here refers to the channel for water loss from the aquifer (Cao *et al.* 2019). An aquifer is a coal mine underground reservoir water supply. How to judge the water supply channel and carry out effective regulation is the basis for realizing the operation of coal mine underground reservoirs. For this reason, it is necessary to conduct research by analyzing the flow channels of aquifers

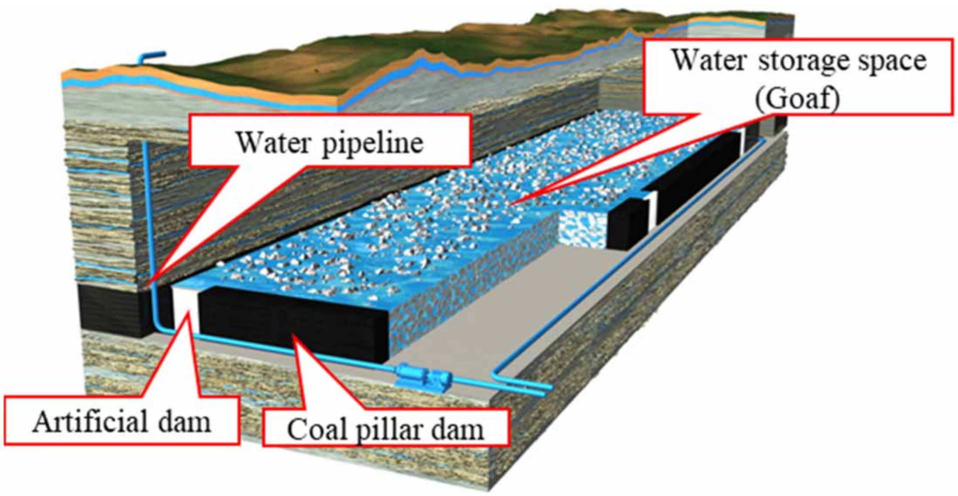

Figure 1 | Schematic diagram of coal mine underground reservoir.

in the process of coal mining. On this basis, the replenishment capacity of the aquifer is analyzed, which provides a basis for the prediction of underground reservoir water in coal mines.

According to the 'three belts' theory of overlying strata, the aquifers are generalized into three types: the first is the lower aquifer, the second is the intermediate aquifer, and the third is the upper aquifer. The generalized types are shown in Figure 2. The specific meaning is as follows:

(1) Lower aquifer means that the aquifer occurrence location is within the water flowing fractured zone, and the water flowing fracture completely destroys the integrity of the aquifer, so that water resources in the aquifer flow into the goaf along the fracture.
(2) Intermediate aquifer means that aquifer occurrence location basically coincides with the development height of the water flowing fractured zone. The destruction of the aquifer by the water flowing fracture is between destruction and stability. In other words, the extent of damage to the aquifer by the mining action is limited, and there is a small water loss in the aquifer along the fracture.
(3) Upper aquifer means the aquifer occurrence location is beyond the development height of the water flowing fractured zone. That is, mining cannot cause damage to the aquifer. The water resource in the aquifer maintains the original state after the coal seam mining, and no water loss occurs.

As we all know, coal seams in western China are very thick and have a shallow burial depth, and water flowing fractures will basically develop to the surface, causing loss of water resources in underground aquifers and shallow aquifers. Therefore, both lower aquifers and intermediate aquifers exist in terms of aquifer types in shallow coal seams (Gu & Zhang 2012; Ju *et al.* 2017; Cao *et al.* 2019). Hence, it can be called water-rich aquifer conditions. In fact, the aquifer in the overlying strata of the coal measure does not exist as a single layer, but multiple aquifers complement each other, demonstrating complex hydraulic connections between each other. Therefore, the generalized model can simplify the complex aquifer occurrence status by classifying multiple aquifers with similar conditions according to the development height of the water flowing fractured zone. This not only simplifies the research model, but also clarifies replenishment source in the water storage of the goaf to a certain extent.

According to the hydrogeological conditions and field experience of Shendong mining area, this paper sets up two aquifers in the numerical simulation model during the research process, and conducts detailed research on the change law of the two aquifers after mining operations in an attempt to understand the main replenishment source in water storage of goaf, thus providing a basis for key technologies such as water source prediction of coal mine underground reservoir.

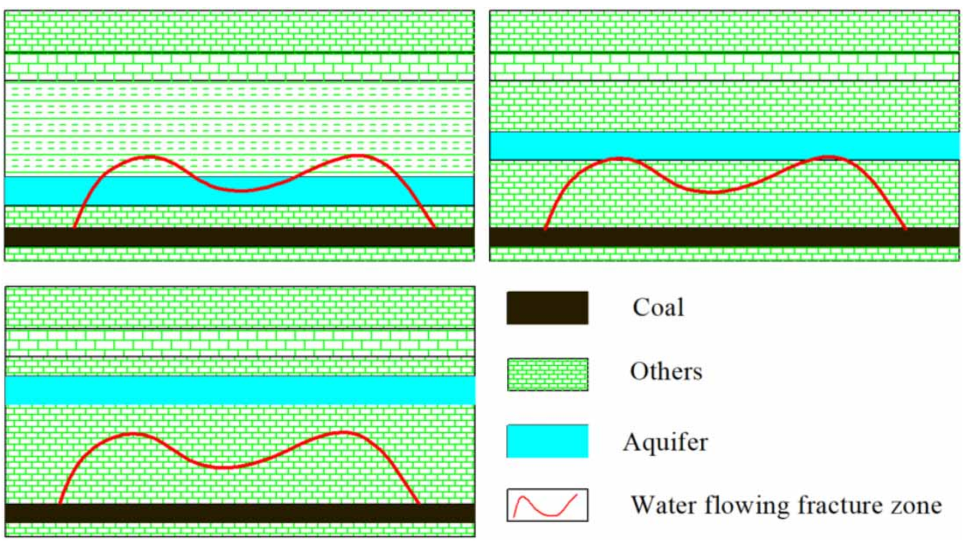

Figure 2 | Generalized classification of coal-water occurrence relationship in shallow coal seams.

NUMERICAL MODEL ESTABLISHMENT AND RESULT ANALYSIS

Establishment of numerical model based on generalized classification

Bulianta coal mine is located in the middle of Shendong mining area. The main coal seam is No. 1-2 coal seam. The average thickness of the coal seam is 7.44 m. Full-seam and fully-mechanized coal mining and equipment with super mining height is adopted. The maximum mining height is designed at 8.0 m. There are mainly two aquifers in the upper part of the coal seam, namely the Quaternary aquifer and the lower Cretaceous Zhidan Group aquifer. The aquifuge is located on the top of the lower Jurassic Yan'an Formation, with an average thickness of 7.28 m, and the lithology is mainly mudstone, sandy mudstone. To analyze water source during the construction of coal mine underground reservoir after the mining of No. 1-2 coal seam, it is necessary to study the impact of mining on the aquifer. Based on the discrete and fluid model of UDEC software, this study conducted numerical simulation analyses based on No. 1-2 coal seam and aquifer occurrence state of Shendong Bulianta coal mine and a numerical analysis model (as shown in Figure 3) was constructed to analyze the influence of coal mining on the aquifer. Then, we studied the influence of different coal–water occurrence modes on the water source of coal mine underground reservoirs. The physical and mechanical parameters of each rock layer of the model are detailed in Table 1. The size and basic parameters of each rock layer in the model are selected as follows:

① Model size: According to the average burial depth of No.1-2 coal, the model height is set to 190 m. Meanwhile, considering the boundary effect and the full mining effect during the advancement of the working face, 60 m coal pillars are left on the left and right sides, and the model length is set to 500 m; excavation step is 10 m/step. ② Mining height selection: According to the actual mining thickness of Bulianta No. 1-2 coal seam, the mining height is set to 8 m. ③ Aquifer: According to the generalized model above, two aquifers are set based on occurrence location of the aquifer, as shown in Figure 3. ④ Monitoring line layout: In the simulation, measuring points are arranged in the lower part of the aquifer (the lower aquifer is arranged with measuring points at the upper and lower parts), the lower part of the aquifuge and the upper part of the coal seam. Hydraulic pressure change characteristics during the mining process are monitored, and related information such as aquifer water level change law and seepage path, etc. is inverted based on hydraulic pressure change characteristics.

Analysis on development status of mining-induced fractures and main replenishment locations

As mentioned above, water loss in coal seam excavation is mainly caused by mining-induced fracture communication with aquifers. Predecessors have carried out much research on this problem, and the research methods mainly focused on

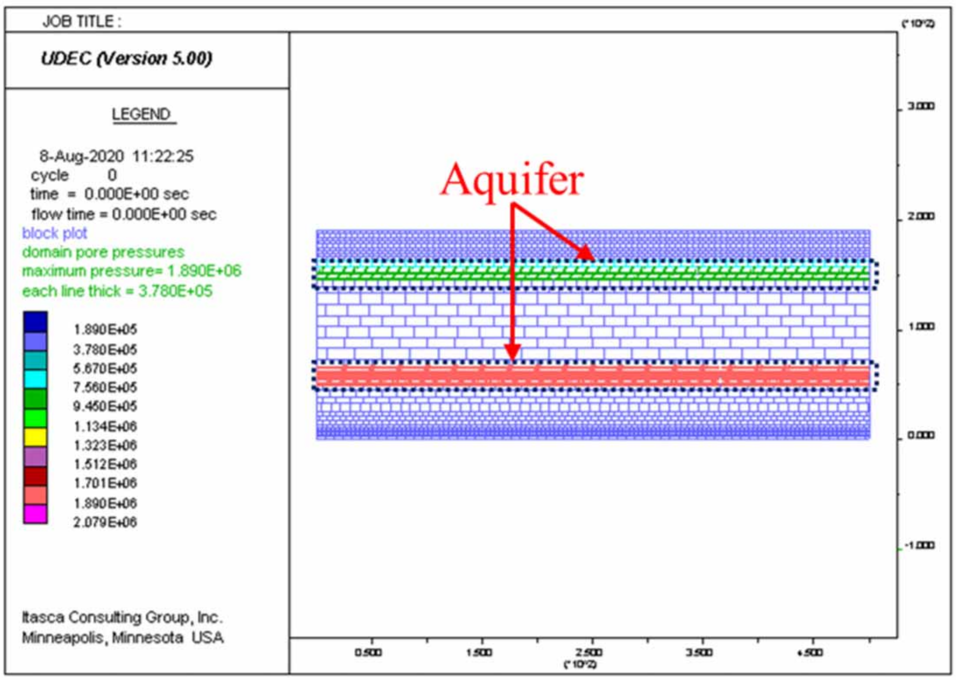

Figure 3 | Numerical simulation generalization model.

Table 1 | Physical and mechanical parameters of rock stratum

Types of rocks	Bulk density kN/m^3	Compressive strength σ_t/MPa	Internal friction angle	Cohesion	Elastic modulus *E*/GPa	Poisson's ratio μ	Permeability coefficient cm/s
Aeolian sand	15.8	–	20	0.02	–	–	1×10^{-9}
Conglomerate	23.9	45.3	39	7.10	33	0.25	3×10^{-4}
Sandy mudstone	22.4	22.8	38	6.32	23	0.28	1×10^{-11}
Siltstone	23.5	40.6	38	7.07	35	0.25	2×10^{-7}
Coal	15.1	6.60	30	2.00	14	0.22	1×10^{-6}
Mudstone	22.3	20.7	29	5.55	20	0.30	3×10^{-10}
Fine sandstone	23.4	6.60	38	6.46	13	0.22	1×10^{-8}

numerical simulation and similar simulation. In the process of numerical simulation, predecessors mainly evaluated it according to the development height of the water flowing fractured zone, and rarely considered the relevant information of the aquifer. This study intended to analyze the development of the water flowing fractured zone combined with the changed characteristics of the aquifer. The replenishment capacity to underground reservoirs in coal mines was analysed by studying the replenishment water volume of the aquifers. Combined with the traditional development analysis method of water flowing fracture zone, this paper focuses on the change of aquifer water pressure under the influence of the water flowing fractured zone, obtains the replenishment capacity of aquifer to the water source of coal mine underground reservoir, and provides support for the key technology of water source prediction of coal mine underground reservoir. Therefore, the development state of mining-induced fractures is a very important factor influencing water storage in goaf. One of the key conditions for water storage in the goaf is water replenishment. Adequate water replenishment is the key to maintaining the safe operation of coal mine underground reservoirs. After the coal seam is mined, the strata moves. In particular, the uneven vertical settlement causes fractures in the strata, mainly tensile fractures at the end of the working face. The fractures have large openings, thus these are likely to become the main channels for water flow. Hence, strata displacement can reflect the failure characteristics of the strata to a certain extent. Figure 4 shows that the strata directly above the working face has a maximum displacement of 8 meters, and the displacement at the open-off cut and terminal mining line shows a 'stepped' incremental change, which gradually increases from both sides of the model to the middle of the working face. The displacement of the surface rock in the middle of the working face is about 7 meters, which is smaller than the maximum rock displacement. It is precisely the difference in strata displacement changes that leads to the formation of water flowing fractured zones. It can be inferred from the strata displacement results that the mining-induced fractures are mainly located in the strata above the open-off cut and terminal mining line.

Predecessors have carried out much research on the development of fractures in shallow coal seams (Song *et al.* 2020; Zhang *et al.* 2011; Ma *et al.* 2015; Chi *et al.* 2019a, 2019b), forming a unified understanding that the impact of mining will normally reach the surface strata, causing surface subsidence and water loss in aquifers. It can also be seen from this simulation that after the mining of the working face, the end part exhibits layer separation in addition to big displacement difference. The farther the separation layer is from the working face, the smaller the change is the change. At the same

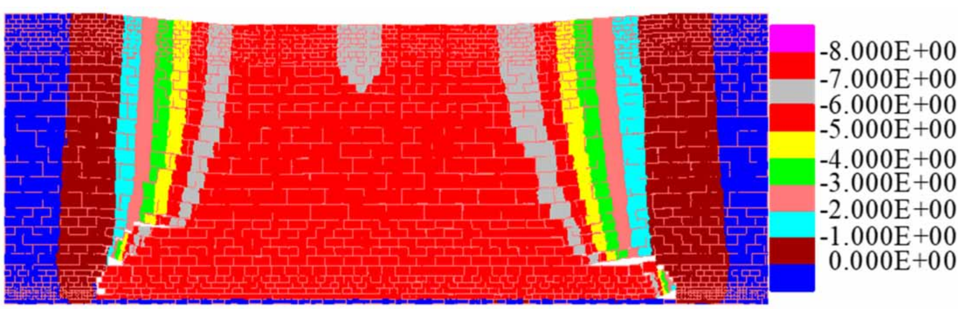

Figure 4 | Vertical displacement result.

time, part of the strata did not fully collapse in the end part, but 'bit' with the coal wall to form a 'triangular area', which was very beneficial for water storage after the construction of the coal mine underground reservoir.

To further analyze water replenishment of coal mine underground reservoirs, it is necessary to confirm the water replenishment channel. Therefore, studying fracture development characteristics under mining action is the basis for clarifying water replenishment. The simulation results show (Figure 5) that the top of the working face acts as the main area for fracture development. Located above the working face in an inverted trapezoidal distribution, fractures develop in both vertical and lateral directions. By comprehensive analysis of the displacement in Figure 4, it is possible to determine that strata of the upper part serve as the major water flowing fractured zone. When water is stored in the goaf, this part acts as the main channel for water replenishment. In addition, it can be seen from the simulation results that the middle of the working face has a worse fracture development degree than both sides, as the horizontal and vertical fractures are poorly developed under difference in rock strength, so it can be regarded as the secondary channel for water replenishment of coal mine underground reservoirs.

Combining the strata displacement and fracture distribution characteristics, water pressure distribution after mining is analyzed to further determine the water replenishment area of the coal mine underground reservoir (Figure 6), thus providing the basis for the prediction of water storage in the goaf. Seen from the water pressure distribution cloud chart, the 'triangular area' at the end of the working face has relatively high water pressure. The water pressure of the strata above the middle of the working face is mainly distributed in the lower part of the aquifer, with only a small part of the water pressure spreading over the goaf. There is more water pressure on both sides of the end than the middle part. On the whole, water pressure distribution presents a 'hump' shape, with water pressure 'converging' in the 'triangular area' and becoming the main 'replenishment point' of underground reservoirs.

In summary, after the coal seam is mined, the overburden stress is redistributed, with fractured zone formed after strata movement and breakage. The tensile fracture in the overlying strata at both ends of the working face is the main channel for water loss from the aquifer. The coal mine underground reservoir is constructed to store and utilize the lost water

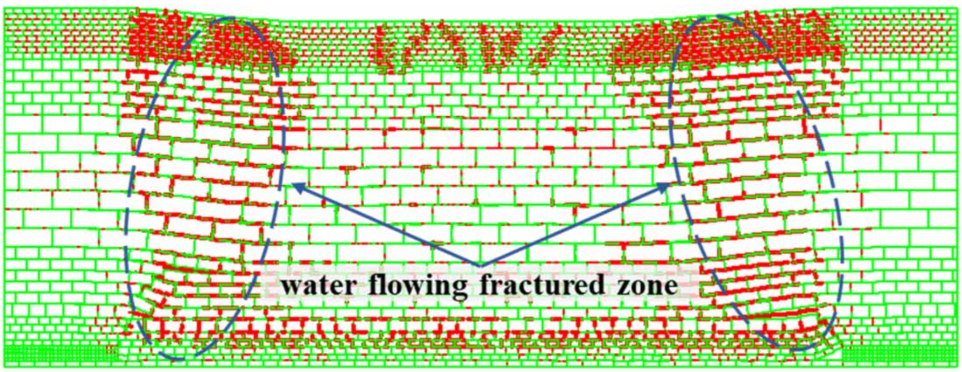

Figure 5 | Fracture development status.

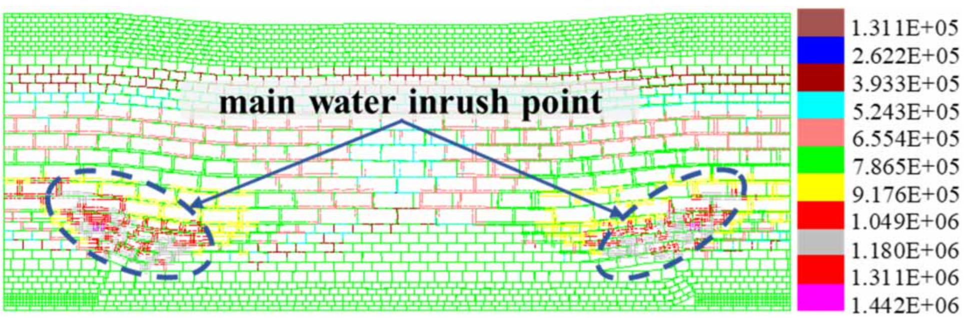

Figure 6 | Main water gushing points.

resources. Hence, the water flowing fractured zone is the main replenishment channel for the reservoir water source and the basic condition for safe movement of the reservoir.

Analysis on the flow state and characteristics of the underground water resources after coal seam excavation

Due to the shallow burial depth of coal seams in western China's mining areas, water replenishment to the coal mine underground reservoirs mainly comes from the aquifers above the coal seams. In particular, the mine water in the Ordos area mainly comes from Quaternary pore water and bedrock fracture water, so water pressure in the aquifer basically forms non-confined aquifer. Therefore, water level changes in the aquifer can be analyzed according to the water pressure change characteristics in the measuring point, and the dynamic change law of the water level before and after the mining can be further analyzed based on the aquifer change characteristics under the mining action. In this way, it is possible to better analyze change characteristics of water resources under mining action. The water pressure change laws of aquifer, coal seam roof and aquifuge are described in the following sections.

Analysis on the influence law of coal seam mining on aquifer

With the continuous advancement of the working face, the mining-induced fracture opens and closes alternately, presenting periodical increase and decrease in water conductivity. Therefore, water pressure in the overlying strata will increase and decrease. Moreover, water conductivity of the water-flowing fracture exhibits strong regional characteristics. Under greater opening of the fracture, water conductivity is stronger. In addition, the occurrence location of the aquifer and the coal seam affects the change of water resources in the aquifer. Generally, an aquifer closer to the coal seam is more affected by mining-induced fracture, giving rise to more water loss and more abundant water replenishment to the coal mine underground reservoir.

It can be seen from the simulation results of three parameters: the development of water flowing fractured zone, the change of aquifer water pressure and displacement (Figures 4–6), after the mining of the working face, water pressure at different locations under the aquifer increases and decreases, with magnitude of change tending to decrease as the distance between the coal seam and the aquifer increases. Water pressure of the lower aquifer changes more than that of the upper aquifer, and the upper water pressure of the lower aquifer also changes with the advancement of the working face. When the working face advances to about 100 m, water pressure experiences great fluctuations, indicating that the lower aquifer is 'replenished' by the upper aquifer. On the whole, water pressure at different locations exhibits a trend of 'rising' with the continuous advancement of the working face, suggesting that the mining-induced fractures are closed with the continuous advancement of the working face, resulting in a decrease in the water passing capacity (Figure 7).

The simulation results revealed that aquifers at different locations are affected by mining according to certain regularity, and there is certain time effect. Generally, there is a changing law of decrease → increase → decrease → recovery. The water resources of the upper aquifer 'migrate' along the mining-induced fracture to the lower strata or aquifer. The lower aquifer is greatly affected by mining, leading to serious water loss caused by coal mining and abundant water replenishment to the underground reservoir.

Analysis on water pressure change law of the aquifuge

Water pressure change in the aquifuge indirectly reflects the dynamic evolution of opening and closing of the fracture during coal seam mining, which also reflects the flow path of water resources after mining to a certain extent. The water pressure change in the aquifuge is shown in Figure 8. The simulation results indicate that water pressure in the aquifuge after coal seam mining exhibits great periodic change. In particular, when the working face is mined to about 50–200 meters, water pressure appears as hump-like fluctuations. It can be inferred that the aquifuge at this time exhibits large-opening water flowing fractures, so large amounts of water resources flow along the fracture, causing increased water pressure of the aquifuge. With the periodic strata breakage and rotation, the fracture is periodically opened and closed, resulting in periodic increase and decrease of hydraulic pressure. In addition, some fractures cannot be completely closed, forming 'permanent' fractures. These fractures become the main channel of mine water and the main water replenishment source for coal mine underground reservoirs.

In general, after the coal seam is mined, the overburden stress is redistributed, and the periodic breakage and closure of the overlaying strata cause periodic replacement of the aquifer water loss channel. Under greater impact of mining on aquifuges, the fracture opening is greater, and the water loss of aquifer is more severe. With it, water pressure change law gets more and more complicated during the advancement of the working face. The difference in water pressure change of the same

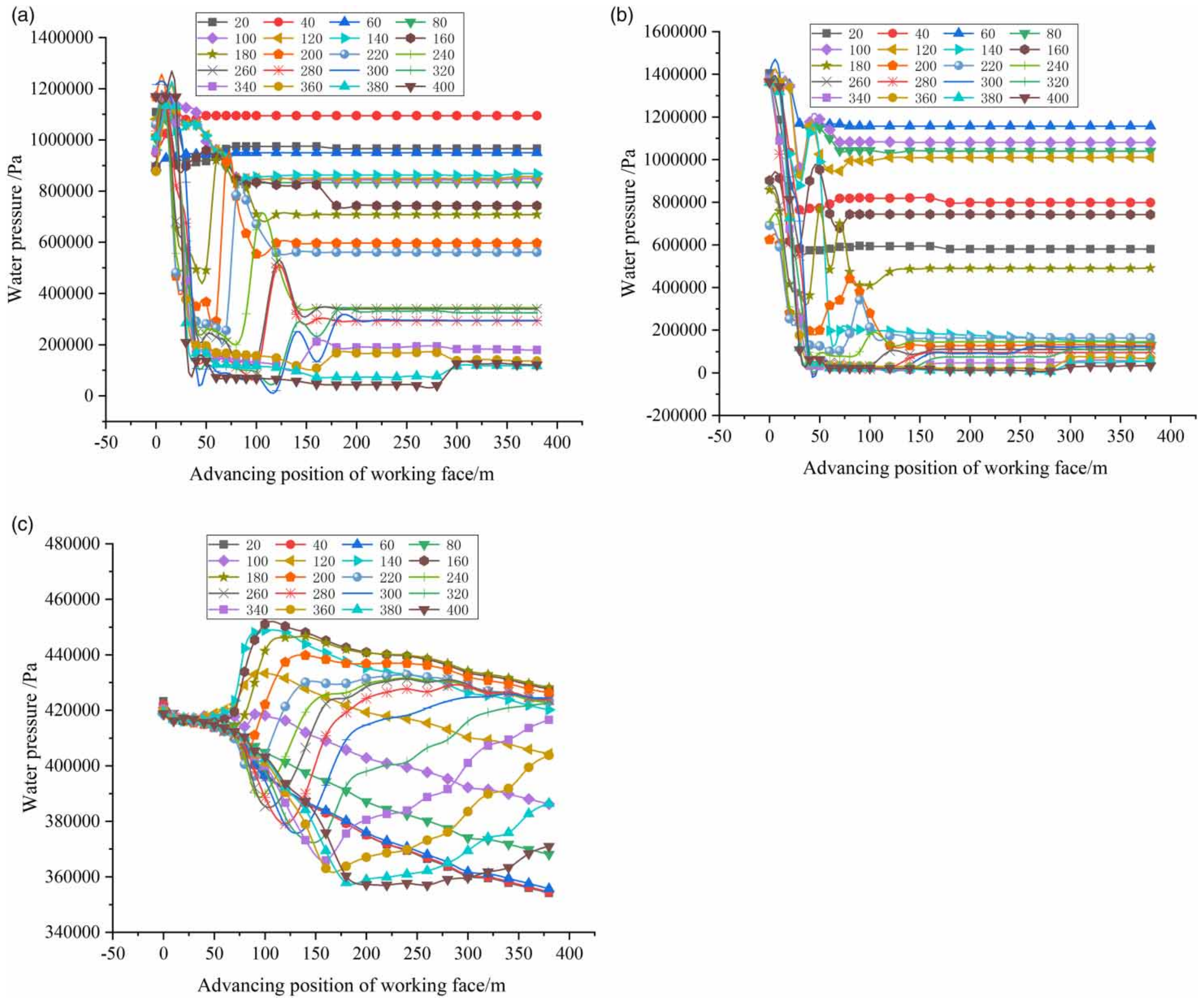

Figure 7 | Aquifer change law. (a) The upper part of the upper aquifer. (b) The bottom part of the upper aquifer. (c) The upper part of the lower aquifer.

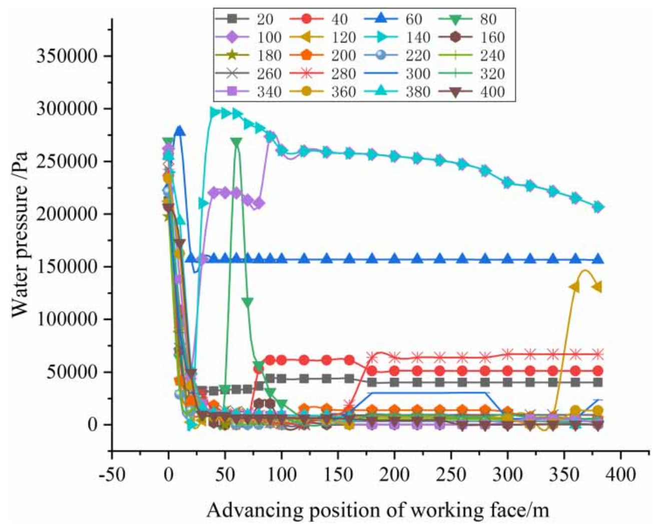

Figure 8 | Change law of aquifuge.

measuring point reflects the difference in the degree of fracture opening of the aquifuge or difference in water conductivity. Under greater water pressure, more water flow is allowed through the fracture and the fracture has a greater opening, which is more beneficial to the water source protection of the coal mine underground reservoir. Combining water pressure change characteristics in the aquifer, it can be inferred that a stable 'water gushing point' is formed at about 100 m away from the open-off cut. The distance between the aquifer and the coal seam exhibits obvious time-dependent characteristics in terms of water resource damage, while the separating ability of the aquifuge determines the water replenishment capacity of groundwater reservoirs to a certain extent.

Analysis on the water pressure change law of coal seam roof

To characterize water replenishment of different types of aquifers to coal mine underground reservoirs, water pressure changes at the coal seam roof are analyzed. Combining the development of water flowing fractured zones and water pressure change law of the aquifer, it can be seen that the open-off cut and terminal mining line are the main water replenishment points of the coal seam roof. The replenishment source mainly comes from the lower limit aquifer. Water pressure change of the coal seam roof is not a result of simple superposition of two aquifers, which indicates that water resources in the upper aquifer have not completely flowed to the goaf, but are 'transferred and stored' within the strata. It can be seen from Figure 9 that water pressure in the coal seam roof exhibits significant increases near the cut-off cut and the terminal mining line, but smooth water pressure changes are shown in the middle of the working face, which further proves that both ends of the working face are the main location for water replenishment of coal mine underground reservoirs.

Combining the above research results on the development of water flowing fractured zone, it can be seen that, after excavation of the working face, there is significant increase in water pressure at the open-off cut and terminal mining line of the working face, indicating that fracture at both ends of the working face has a large opening that becomes a stable water outlet, while the middle part has closed fractures due to the strata re-compaction. As the upper strata of the working face are constantly replenished by the water source of the aquifer, the water pressure increases → decreases → increases periodically. Water pressure change in the coal seam roof can directly reflect the damage of different types of aquifers under mining action and its ability to replenish the water source of the coal mine underground reservoir. Figure 6 reveals a direct relation between replenishment capacity of aquifers to coal mine underground reservoirs and 'coal–water' occurrence relationships. With closer distance to the coal seam, the replenishment capacity is stronger, and the downward flow time of water resources is relatively advanced. When there are multiple aquifers above the coal seam, the aquifer located between the caving zone and the fractured zone is the primary 'replenishment aquifer' of coal mine underground reservoir, while the upper aquifer constantly replenishes the lower aquifer under the action of the fracture in a way affected by the development height and opening of the fracture.

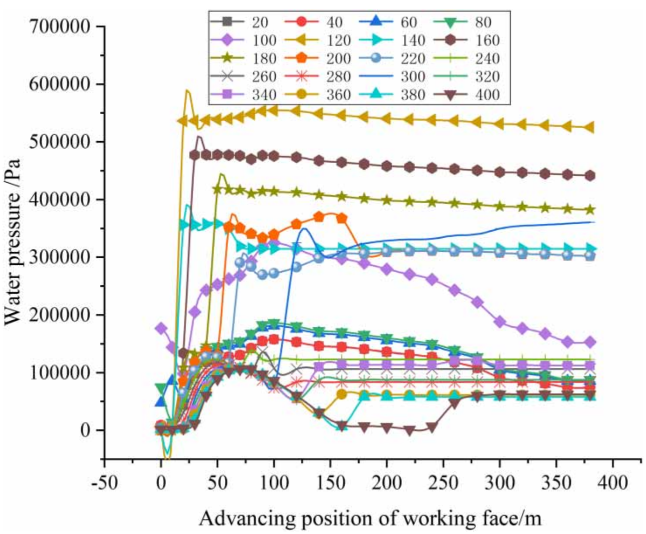

Figure 9 | Change law of coal seam roof.

Prediction and case analysis of water source and water volume in goaf

The water source of coal mine underground reservoir mainly comes from the water resources in the aquifer. In the simulation results, the water pressure change in coal seam roof reflects the status of aquifer replenishment to the coal mine underground reservoir. In our further analysis of the degree of water replenishment to the coal mine underground reservoir by different types of aquifers, the simulation results revealed that, after the coal seam is mined, stable water outlets will appear at the open-off cut and terminal mining lines. The mining-induced fracture generated in this area has a large opening that becomes one of the stable water sources of underground reservoirs. The above research results indicated that the coal–water occurrence relationship exerts a great influence on the water pressure of coal mine underground reservoirs. An aquifer farther away from the coal seam has more unstable replenishment to the underground reservoir. To quantitatively analyze the replenishment capacity of different types of aquifers with regard to coal mine underground reservoirs, according to Darcy's law calculation method, this paper views the water inflow V in a variable relationship $V = \sum v \cdot dS$ between the flow velocity v, the flow channel area S and time t, where, V is the water inflow, m^3/h; v is the water velocity, m/s; S is the cross-sectional area of the water flowing through the strata (in the inclination direction of roof coal seam along the working face), m^2. The water velocity monitoring results in the monitoring point are shown in Figure 10. Based on the development degree of the main fractures in the mining process, the cross-sectional area of seepage is derived according to the actual working face width, and the final calculation of the water inflow is shown in Figure 11. The working face width is calculated as 200–300 m, and the water inflow is about 493–739 m^3/h.

According to the 2016–2019 water inflow data statistics of Bulianta coal mine, the normal mine-wild water inflow of Bulianta coal mine is about 575 m^3/h, and the maximum water inflow is about 799 m^3/h, of which the average value is 563 m^3/h in 2016, 588 m^3/h in 2017, 568 m^3/h in 2018, 575 m^3/h in 2019. The actual water inflow during the mining process of No. 1-2 coal seam in Bulianta coal mine is about 400 m^3/h, which is within 10% deviation from the simulated value. Therefore, this simulation can better reflect water replenishment capacity of the coal mine underground reservoir. In the actual application process, analysis is made according to the occurrence state of the aquifer (upper, lower, middle), and the location of the primary water flowing fracture is determined based on the simulation result to obtain the main water replenishment channel. According to the water velocity and working face parameters, the mine water inflow amount is finally obtained to provide a calculation basis for water replenishment of coal mine underground reservoirs.

RESULTS AND DISCUSSION

Mine water protection and utilization has always been an important issue that needs to be solved in the process of coal mining in mining areas. In particular, in recent years, all sectors of society have paid increasingly more attention to the ecological environment, forcing enterprises to continually carry out technological innovations to fundamentally solve the problem of water resources protection and utilization, thus achieving the goal of 'zero discharge' and 'optimal utilization'

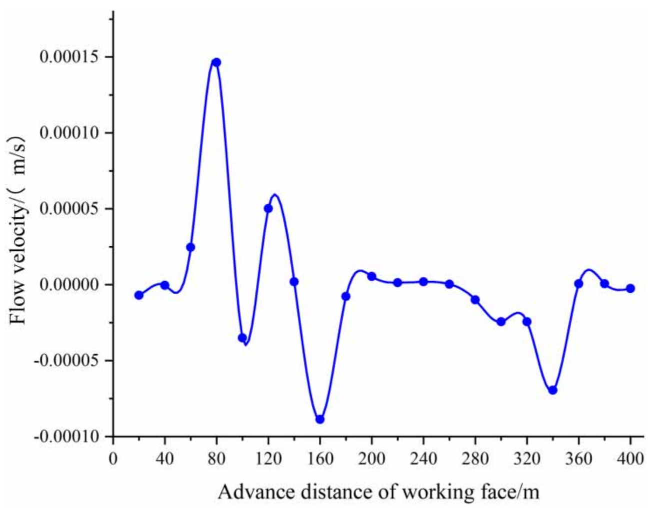

Figure 10 | Water velocity change law of roof.

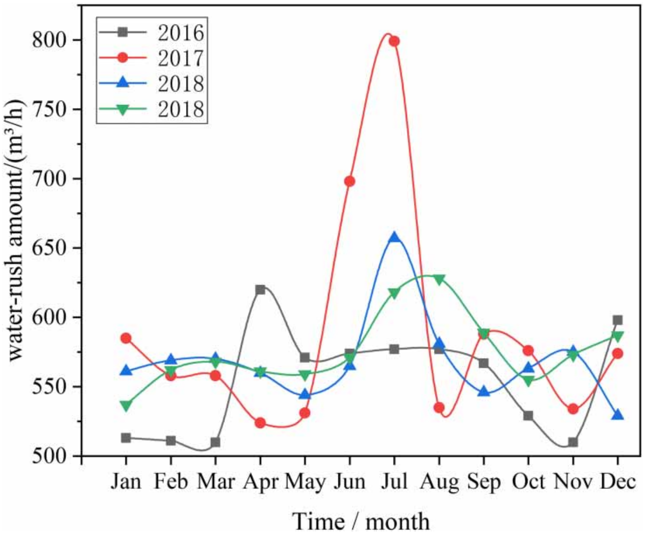

Figure 11 | Changes in mine-wild water inflow over the years in Bulianta coal mine.

of mine water (Hannan & Broz 1976; Cao *et al.* 2019; González-Quirós & Fernández-Álvarez 2019; Li *et al.* 2019; Zhao *et al.* 2019; Jiao *et al.* 2020). Underground reservoir has the characteristics of no land occupation, large storage capacity and small evaporation loss (Hannan & Broz 1976, Menéndez *et al.* 2019; Fan *et al.* 2020; Menéndez *et al.* 2020; Song *et al.* 2020; Wang *et al.* 2020a, 2020b, 2020c, Yao *et al.* 2020; Yang *et al.* 2020). Shendong mining area of China took the lead in carrying out the practice of water resource preservation during mining, covering the storage, purification, and recycling of groundwater reservoir water resources, which reasonably solves the problem of coordination between ecological protection and coal mining in the mining area, and achieves significant economic and social benefits (Gu 2015; Cao *et al.* 2019). Focusing on the key links and technologies in coal mine underground reservoir construction, Gu (2015) and Gu *et al.* (2016), summarized and refined the six key technologies for coal mine underground reservoirs, thoroughly studied the core contents of water source prediction, reservoir site selection, storage capacity design, etc., and formulated corresponding industry and enterprise standards. Through field measurement and theoretical analysis, some scholars evaluated the adaptability of underground reservoirs from the perspective of water flowing fractured zones, and put forward suggestions on the formulation of technical standards for coal mine underground reservoirs. There are also some scholars who conducted in-depth research on construction technology system of underground reservoirs through experimental research and theoretical derivation, put forward research methods for key technologies such as storage capacity calculation and dam strength assurance (Yao *et al.* 2018; Li 2019; Liu *et al.* 2019). Cao *et al.* (2014), Yao *et al.* (2018, 2019); Liu *et al.* (2019) adopted numerical simulation and similar simulations to study mine water inflow, underground reservoir construction technology, and groundwater reservoir monitoring methods, proposing solutions based on actual cases. Based on the construction technology and experience of coal mine underground reservoirs, Li (2019) tried the construction of underground reservoirs in open-pit coal mines, and built demonstration projects in large-scale coal power bases such as Shengli coal mine and Baorixile coal mine. These studies mainly investigated and studied the stability of coal mine underground reservoirs from the engineering point of view, still depending on prediction and analysis of mine water inflow in research on the water source of coal mine underground reservoirs.

The research on the key links such as water source prediction and replenishment of newly built underground reservoirs is passive, which limits the development of other key links in newly built coal mine underground reservoirs. The above research results are mainly based on traditional laboratory analysis and numerical simulation methods. Research on the changes of aquifers (especially water pressure and water velocity) during coal seam mining is rarely conducted, and the research on reservoir water source prediction and replenishment problems has not been explored in depth. The research on reservoir water source issues is still mainly based on on-site drilling, mine water inflow and other methods, which failed to achieve the purpose of predicting and analyzing before the construction of the reservoir. This paper is based on this research gap, generalizes and classifies the aquifers based on the occurrence location of the aquifers and the development height of the water flowing fractured zone, and studies the water replenishment capacity of various types of aquifers to the reservoir. It provides support for the key technology of water source prediction in the construction of coal mine underground reservoirs.

In fact, for coal mine underground reservoirs there is, a new type of underground hydraulic structure, the biggest feature is that it uses the goaf after coal seam mining to store water. Coal seam mining not only causes changes in the overburden structure, but also affects replenishment condition and hydraulic connection of groundwater aquifer. Since most groundwater in the Ordos area is bedrock fracture water, this part of water resources is difficult to be exploited and used on a large scale under conventional technical means. Nevertheless, coal mine underground reservoirs use mining-induced fracture as water channels to achieve large-scale utilization of bedrock fracture water. Meanwhile, mine water and shallow aquifer water produced during coal mining are simultaneously stored and purified for ecological, production and living use in the mining area, which greatly solves the water use problem of coal enterprises in water-scarce areas. At the beginning of the construction of coal mine underground reservoirs, storage capacity design is needed to ensure that water level and storage capacity of the underground reservoir are maintained within a safe range, so that coal mine underground reservoirs are safe and reliable. Therefore, water source prediction in coal mine underground reservoirs is the top priority throughout the entire life cycle of coal mine underground reservoirs. Previous studies have been mainly based on actual monitoring of mine water inflow. Although it provides a monitoring basis for water replenishment of coal mine underground reservoirs, in the long run, this method still lacks certain scientific method. Many scholars have carried out extensive simulation studies on the impact of coal seam mining on aquifers. In the analysis, aquifers are mainly simplified, that is, only aquifers of a certain thickness are considered (Fan 2017; Li *et al.* 2018; Chi *et al.* 2019a, 2019b, González-Quirós & Fernández-Álvarez 2019). In fact, the underground aquifer is not just uniformly thick, but there are multiple complex hydraulic connections with each other. Although it is difficult to invert the actual existence of aquifers during the simulation process, aquifers can be generalized into several categories for research based on certain rules. For this reason, based on the development height of the water flowing fractured zone, this paper generalizes and classifies occurrence location of the aquifers, analyzes the change laws of different types of aquifers under mining actions and their ability to replenish coal mine underground reservoirs. The research results mean good reference significance for construction and safe operation of coal mine underground reservoirs.

This paper analyzes the types of aquifer water replenishment sources in the process of coal mining. It simplifies the actual complex and changeable aquifers, avoids the previous single analysis of aquifers, and provides a basis for other similar studies. On this basis, this paper organically combines the development of water flowing fractured zones and the water pressure change, and analyzes the source and size of the water replenishment of the underground reservoir in the coal mine from the perspective of the law of the water pressure change. The results showed that the mixed aquifer will cause a large number of water sources to enter the goaf in the process of coal seam mining, and it is an important supply source of coal mine underground reservoirs. The lower aquifer has a strong replenishment capacity to the aquifer after coal seam mining, but this is less than the mixed aquifer. When the mining-induced fracture of the upper aquifer is not developed to the aquifer, it basically does not cause damage to the aquifer, the water source in the aquifer will not flow downward, and the underground reservoir of the coal mine cannot be replenished. In the process of practical application, the aquifer can be analyzed according to the generalized model proposed in this paper, and the development of a water flowing fractured zone can be studied according to the numerical analysis model, to obtain its replenishment capacity to the coal mine underground reservoir and guide the construction and safe operation of the coal mine underground reservoir.

CONCLUSION

This paper generalizes the types of aquifers based on the discrete element fluid–solid coupling numerical simulation model. Water replenishment channel of coal mine underground reservoirs is determined, water replenishment capacity of coal mine underground reservoirs is predicted and evaluated when water-rich aquifer is subject to the influence of coal seam mining. The following specific conclusions are drawn:

(1) Development of water flowing fractured zone to aquifer and formation of water-conducting channel is one of the key conditions for the loss of water resources in the aquifer. Based on the occurrence location of the aquifer and the development height of the water flowing fractured zone, the overlying aquifer of the shallow coal seam is generalized into three types: the lower aquifer located between the caving zone and the fractured zone, the upper aquifer above the fractured zone, and mixed aquifer involving the above two cases.
(2) The dominant water flowing fractured zone is located at both ends of the working face, mainly tensile fracture that acts as the main channel for water replenishment to the coal mine underground reservoir; the fracture in the middle of the

working face is mainly q horizontal fracture (or separated layer fracture), which is poorly developed compared to both sides as the secondary channel for water replenishment of coal mine underground reservoirs.

(3) The results of analyzing the water pressure changes in aquifers, water barriers, and coal roofs show that the aquifer has a certain time effect under the influence of mining, and it shows a law of increasing and decreasing alternate changes with time. The farther the location of the aquifer is from the coal seam, the longer it is affected by mining, the lower the damage degree, and the weaker the supply to the underground reservoir of the coal mine.

(4) Taking Bulianta coal mine as an example, the calculated mine water inflow of different models is about 493–739 m^3/h, and the error with the measured results (Class III aquifer) is less than 10%. The research results provide a basis for the water supply of underground reservoir in coal mines, and provide an idea for the prediction of mine water inflow.

DECLARATION OF COMPETING INTEREST

No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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