

Optimization of group borehole drainage of a mine above a high pressure, low permeability aquifer

Haifeng Lu*, Yuan Zhang, Manman Zhang and Guifang Zhang

School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, China

*Corresponding author. E-mail: hflu@aust.edu.cn

Abstract

Drainage to lower water pressure is an effective measure for preventing and controlling water ingress when mining above a confined aquifer. The deep limestone aquifer in the Huaibei mining area, China, generally has high pressure, low permeability and variable water abundance, so it is difficult to meet single-borehole drainage requirements. In order to achieve good drainage, and take into account engineering and environmental protection requirements, a multi-objective optimization model of group borehole drainage was established. The model takes the minimization of single-hole flow and borehole numbers as the objective functions, and the drawdown in drainage boreholes and the water level control point as the constraint conditions. The particle swarm optimization algorithm was used to solve the model. The results indicate that, for a low permeability aquifer, measures such as using partially penetrating wells, increasing the number of drainage boreholes appropriately and reducing individual borehole yield have good drainage effects. The extent of drilling and amount of drainage are also relatively small. This is all to the good for the drainage. When the optimization results were applied to coal-face drainage in Huaibei the outcome was good.

Key words: aquifer permeability, drainage to lower water pressure, floor water inrush, multi-objective optimization

HIGHLIGHTS

- The multi-objective optimization model of group borehole drainage for low permeable aquifer is established. Under the premise of ensuring the safety of coal mining, the research results protect the groundwater resources to the greatest extent and reduce the amount of drilling work.
- The optimization model has certain guiding significance for the determination of single-hole flow, the degree of drainage borehole penetrating the aquifer and the number of boreholes when it is applied to the drainage of low permeability aquifer.
- The research results are of guiding significance to avoid floor water inrush during mining above a confined aquifer.

INTRODUCTION

Coal is a reliable and affordable energy source in many countries; for example, China, and supports about 40% of world electricity generation. Coal production, however, is constrained by various problems, including water inrushes to the working face during mining (Yuan 2019). Most of China's coal comes from North China type coal fields at present and recently, with increasing mining depth, the threat from the karst fissure water from Carboniferous Taiyuan formation and Ordovician limestone has increased to mining of the lower coal group (Wu *et al.* 2014, 2017). According to

incomplete statistics, most major water inrush incidents in China in recent years have been caused by karst fissure water in the coal seam floor penetrating the working face. Many scholars have studied the prevention and control of karst fissure inrushes with fruitful results. They have produced forward theories including 'water inrush coefficient' (Guo & Liu 1989; Li *et al.* 2018), 'key stratum' (Qian *et al.* 1995, 2003; Lu *et al.* 2018), 'progressive intrusion' (Wang *et al.* 1996; Lu *et al.* 2015), 'plate model' (Zhang 2005; Kostecki & Spearing 2015) and 'down three zone' (Li 1999; Sun *et al.* 2012; Yin *et al.* 2016), etc., which all reveal water inrush mechanisms from different aspects. All of these theories have played a positive guiding role in mine safety improvements. The rock mass is so complex, however, that major water inrush incidents still occur from the floor from time to time.

Huaibei coalfield is of the North China type and mining of No. 10 coal seam is generally threatened by the confined waters of the underlying Taiyuan Formation limestone. As mining goes deeper, the aquifer water pressure and risk of water inrush increase. At present, the aquifer is commonly drained at a certain flow by constructing drainage boreholes on the ground or in the roadway. This can reduce the confined water level to below the 'safe water head', resulting in safe mining. The method is economical and easy, so it has been used widely in mining the Lower Coal Group in the Huaibei mining area, with good results.

Previous studies have shown that 'high water pressure and low permeability' are characteristics of the deep Taiyuan Formation limestone aquifer in the Huaibei mining area (Chen *et al.* 2012; Zheng 2018). Due to the aquifer's low permeability, the aquifer's water pressure decreases rapidly and the water level falls quickly during pumping. The cone of depression is V-shaped and the radius of influence is small. In order to improve drainage, measures like infill drainage boreholes are generally taken, but the increased numbers of drainage boreholes has increased coal mine production costs and, at the same time, drainage has also damaged the groundwater resources, with a serious impact on sustainable development of the mining area. Therefore, in order to achieve safe production, the total volume of water drained and the amount of drilling should be reduced as far as possible, to optimize the balance between safety, economy and environmental benefits. This was the fundamental starting point for the drainage optimization project.

There has been considerable research into water resource management to date (Sulis *et al.* 2011; Wang *et al.* 2012a, 2012b; Dolatshahi-Zand & Khalili-Damghani 2015; Zhao & He 2015; Song *et al.* 2016). However, there are few drainage optimization designs for mining above confined limestone aquifers. Meng *et al.* (2015) established the optimal design model for single-hole drainage and the optimal drainage borehole layout. The limestone aquifer generally has the characteristics of high water pressure, low permeability and uneven water abundance in deep mining, so it is hard to meet the single-hole drainage requirements. There are no reports, however, on the optimization of group borehole drainage in such aquifers. The purpose of this study was to fill this gap, therefore, by optimizing borehole numbers and flow in the group borehole drainage, so that drainage is achieved while the cost of coal mining and degree of environmental damage are reduced effectively. The optimization model proposed can be used to study the design and calculation of group borehole drainage on the basis of the aquifer's hydrogeological characteristics. Because the analytical solution of the draw-down of inclined and/or horizontal wells is relatively complex, the optimization model reported here was established on the basis of the unsteady flow theory of vertical wells.

RESEARCH METHOD

Unsteady groundwater flow into a well

Depending on the degree of aquifer exposure and the water inflow conditions, drainage boreholes can be either fully or partially penetrating. When a drainage borehole is open through the entire thickness of an aquifer, it is fully penetrating, otherwise it is a partially penetrating well (Figure 1).

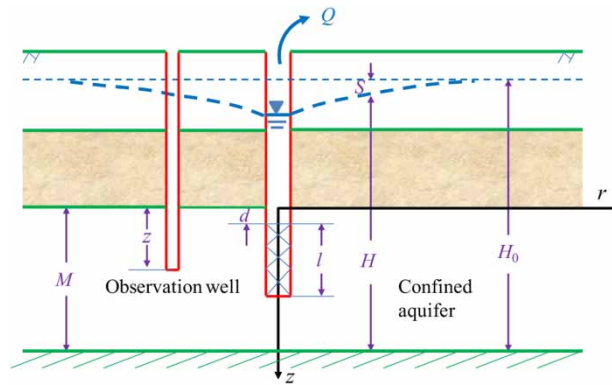


Figure 1 | Schematic diagram of partially penetrating and observation wells in a confined aquifer.

If the confined aquifer fulfills Theis' assumption, when the drainage borehole is partially penetrating and the distance, r , between the observation and drainage wells is $r \leq 1.5 M$, the drawdown is given by Equation (1):

$$S = \frac{Q}{4\pi KM} \left[W(u) + \zeta \left(\frac{l}{M}, \frac{d}{M}, \frac{r}{M}, \frac{z}{M} \right) \right] \quad (1)$$

in which:

$$\zeta \left(\frac{l}{M}, \frac{d}{M}, \frac{r}{M}, \frac{z}{M} \right) = \frac{4M}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{1}{n} \left[\sin \left(\frac{n\pi l}{M} \right) - \sin \left(\frac{n\pi d}{M} \right) \right] \cos \left(\frac{n\pi z}{M} \right) K_0 \left(\frac{n\pi r}{M} \right) \quad (2)$$

$$u = \frac{r^2 \mu^*}{4KMt} \quad (3)$$

$$W(u) = \int_u^{\infty} \frac{e^{-x}}{x} dx = -0.577216 - \ln u + u - \sum_{m=2}^{\infty} (-1)^m \frac{u^m}{m.m!} \quad (4)$$

where Q is the borehole yield (m^3/d), r the line distance between the calculation point and the drainage borehole (m), S the drawdown (m); K the aquifer permeability coefficient (m/d); M the full aquifer thickness (m); μ^* the elastic release coefficient; $W(u)$ the Theis well function; u the independent well function variable; ζ the additional resistance coefficient of non-integrity; d and l respectively are the distance from the confining layer to the top and bottom of the borehole filter (m); z the distance between the confining layer and the bottom of the observation borehole (m); and t the drainage time (d).

Equation (1) shows that there are two parts to the drawdown of a partially penetrating well. The former represents the drawdown of the corresponding fully penetrating well, while the latter represents the additional drawdown caused by the bending of nearby flow lines by the partially penetrating well. When the pumped well is fully penetrating or $r > 1.5 M$, the additional resistance coefficient can be ignored and simplified to Equation (5) for the fully penetrating well:

$$S = \frac{Q}{4\pi KM} [W(u)] \quad (5)$$

When the group borehole drainage flows are Q_1, Q_2, \dots, Q_n , respectively, the drawdown at any point can be calculated using the seepage superposition principle – that is, it is the sum of the

drawdowns caused at this point by each individual drainage borehole – Equation (6):

$$\begin{cases} S = \sum_{i=1}^n \frac{Q_i}{4\pi KM} \left[W(u_i) + \zeta \left(\frac{l_i}{M}, \frac{d_i}{M}, \frac{r_i}{M}, \frac{z_i}{M} \right) \right] \\ S = \sum_{i=1}^n \frac{Q_i}{4\pi KM} [W(u_i)] \end{cases} \quad (6)$$

Optimization problem

Water level control point and safe water level

For mining to be safe, the aquifer's water level is taken below the 'safe head', the key index of mine drainage, by draining it. The value of the 'safe head' is the water head that the coal seam floor can withstand. The lower the safe value, the greater the head reduction needed. Because the coal seam floor can withstand certain water pressure, if the safe water head exceeds the actual water head, mining can be undertaken directly under pressure without discharging water. In actual projects, the water inrush coefficient is generally used to determine the 'safe water head' – Equation (7).

$$p = T_s M' \quad (7)$$

where M' is the distance from the coal seam floor to aquifer roof, that is, the aquifer cap thickness (m); and T_s the critical water inrush coefficient (MPa/m). In the 'detailed rules for the prevention and control of water in coal mines' (China State Administration of Coal Mine Safety 2018), T_s is taken as 0.06 MPa/m in sections with structural damage and 0.1 MPa/m in complete sections; p is the head that the aquifer cap can bear safely (MPa). After calculating p , the safe head can be determined according to the conversion relationship between pressure and head.

In a real drainage project, the working face boundary is taken as the drainage boundary, and the end of the working face is selected as the water level control point within the drainage boundary to calculate the safe water level. The aquifer cap floor's elevation – that is, that of the aquifer roof – H_d – is determined first at each water level control point together with initial water level elevation, H_0 . Then the safe pressure is converted to a safe water level using $H_s = p \times 100 + H_d$. Finally, using $S_s = H_0 - H_s$, the safe drawdown level at each water level control point is determined.

Optimization model

(1) Objective function

Because of the limestone aquifer's high water pressure and low permeability, single-hole flow and the number of drainage boreholes were taken as the optimization model's objective functions, in order to protect groundwater resources to the maximum extent possible. The objective function is expressed in Equation (8):

$$Z = \text{opt}\{Q, n\} \quad (8)$$

The drainage roadway is generalized as a line segment with dip angle θ . When the coordinates of points A and B at its ends are (x_{p1}, y_{p1}) and (x_{p2}, y_{p2}) , the roadway's linear equation $y = ax + b$ can be obtained, where a is the line's slope, b its intercept, and $[x_{p1}, x_{p2}]$ is the abscissa range of the straight line segment. The roadway's total length is L .

The drainage roadway has n equally spaced drainage boreholes; $F_1, F_2, \dots, F_i, \dots, F_n$, that are D apart. The coordinates of any drainage borehole are (x_{ci}, y_{ci}) . The working face has m water level control points –

$C_1, C_2 \dots C_j, C_m$ – the coordinates of any control point are (x_j, y_j) . The distance from any drainage borehole to any water level control point is recorded as r_{ij} . It is assumed that each drainage borehole's yield is the same and $= Q$. The minimum optimization models of Q and n are $\min(Q)$ and $\min(n)$. The drainage borehole and water level control points are shown in Figure 2.

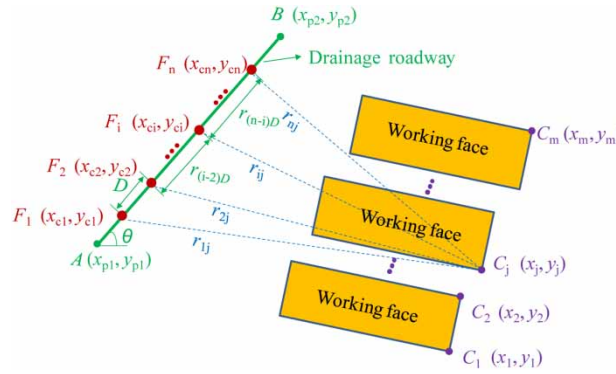


Figure 2 | Drainage borehole and working face arrangement.

On the premise of safe mining, the single-hole flow and the number of boreholes are minimized, and the best drainage borehole position in the roadway will affect the realization of optimization directly.

(2) Constraint conditions

(1) Borehole number

As shown in Figure 2, the roadway's lower left corner is the location of the first drainage borehole (x_1, y_1) . Because drainage boreholes must be arranged along the drainage roadway, they must be within the drainage roadway's bounds. Using the roadway end point coordinates and its straight line equation, the constraint conditions for the number n of drainage boreholes in this group can be written as Equation (9):

$$\begin{cases} n = \left\lceil \frac{L - \sqrt{(x_{p1} - x_{c1})^2 + (y_{p1} - y_{c1})^2}}{D} \right\rceil > 1 \\ 0 < D \leq L - \sqrt{(x_{p1} - x_{c1})^2 + (y_{p1} - y_{c1})^2} \\ x_{c1} \leq x_{p1}, x_{c1} + (n - 1)D \cos \theta \leq x_{p2} \end{cases} \quad (9)$$

(2) Yield

When the drainage borehole water level drops to the aquifer roof (S_{max}), the drainage borehole yield is recorded as Q_{max} and is the maximum value constraint condition of single-hole flow in optimization – that is, the upper limit of flow. If the drainage borehole radius is r_w , and taking account of mutual interference between drainage boreholes, the flow constraints are as follows:

- When the drainage borehole is fully penetrating or partially penetrating but with inter-borehole spacing not less than $D \geq 1.5M$, the i -th drainage borehole is:

$$Q \leq \frac{4\pi KMS_{max}}{W(u_{r_{(i-1)D}}) + \dots + W(u_{r_D}) + W(u_{r_w}) + W(u_{r_D}) + \dots + W(u_{r_{(n-i)D}})} \quad (10)$$

where, $r_{(i-1)D}$ is the distance from the first to the i -th borehole (m), and the other distances are the same as in Figure 2.

- When the drainage borehole is partially penetrating, if the distance $D < 1.5M$, and ignoring the mutual interference of the non-integrity additional resistance coefficient ζ , the i -th drainage borehole is:

$$Q \leq \frac{4\pi KMS_{\max}}{W(u_{r_{(i-1)D}}) + \dots + W(u_{r_D}) + W(u_{r_w}) + W(u_{r_D}) + \dots + W(u_{r_{(n-i)D}}) + n\zeta\left(\frac{l}{M}, \frac{d}{M}, \frac{r_w}{M}, \frac{z}{M}\right)} \quad (11)$$

(3) Drawdown at control points

The drawdown at all control points shall reach the safe drawdown level in order to meet the requirements of safe mining. For the j -th water level control point, the safe drawdown is S_{sj} , and its constraint conditions are as follows:

- When the drainage borehole is fully penetrating, or partially penetrating but $r \geq 1.5 M$, there are:

$$\sum_{i=1}^n \frac{Q}{4\pi KM} [W(u_{ij})] \geq S_{sj} \quad (12)$$

- When the drainage borehole is partially penetrating and the distance r between the water level control point and the drainage borehole is $r \leq 1.5 M$, there are:

$$\sum_{i=1}^n \frac{Q}{4\pi KM} \left[W(u_{ij}) + \zeta\left(\frac{l_i}{M}, \frac{d_i}{M}, \frac{r_i}{M}, \frac{z_i}{M}\right) \right] \geq S_{sj} \quad (13)$$

Model solving

Because of the problem of draining the high pressure, low permeability aquifer, a dense pattern of drainage boreholes is generally used to ensure the safety of the whole working face. However, if too many boreholes are drilled, mining costs will rise while, if the number is reduced, the yield from each must be increased. Equally, due to the low permeability, the yield from any one borehole should not be too large, or the effect of drainage is poor. The optimization objective, therefore, is to use as few drainage boreholes as possible while minimizing the single-hole yield under the constraint conditions – that is, there are multiple objectives. For this study, the multi-objective particle swarm optimization (MOPSO) algorithm proposed by Coello & Lechuga (2002) was used. It extends particle swarm optimization to multi-objective issues. MOPSO is recognized as a classical approach. At its core is choosing the best combination among the multiple mutual restricting objectives. The establishment and calculation procedures are shown in Figure 3.

EXAMPLE APPLICATION AND DISCUSSION

Engineering background

Suntuan coal mine is in the southwest of the Huaibei coalfield, in northern Anhui Province, China. The No. 10 coal seam is 35 to 55 m above the top of the confined Taiyuan Formation limestone aquifer (Figure 4). The formation comprises 12 limestone horizons (L_1 - L_{12}) in the coalfield, and its total thickness is 85 to 130 m. Of this, the limestone horizons account for 45 to 70 m, or about 60% of

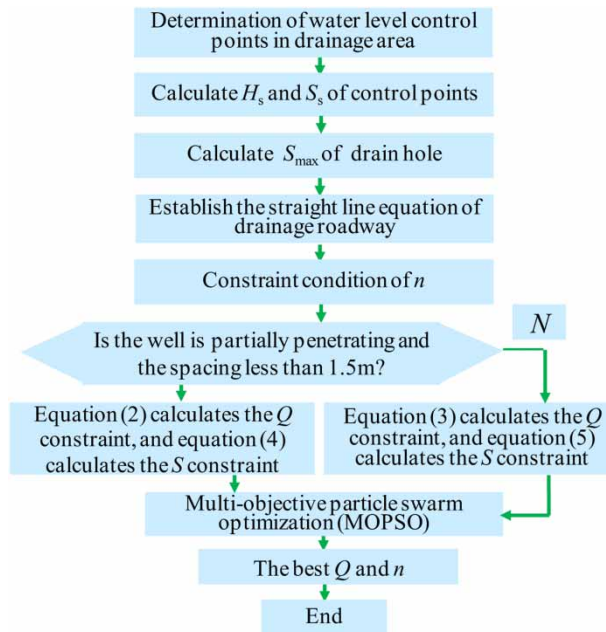


Figure 3 | Optimization model flowchart.

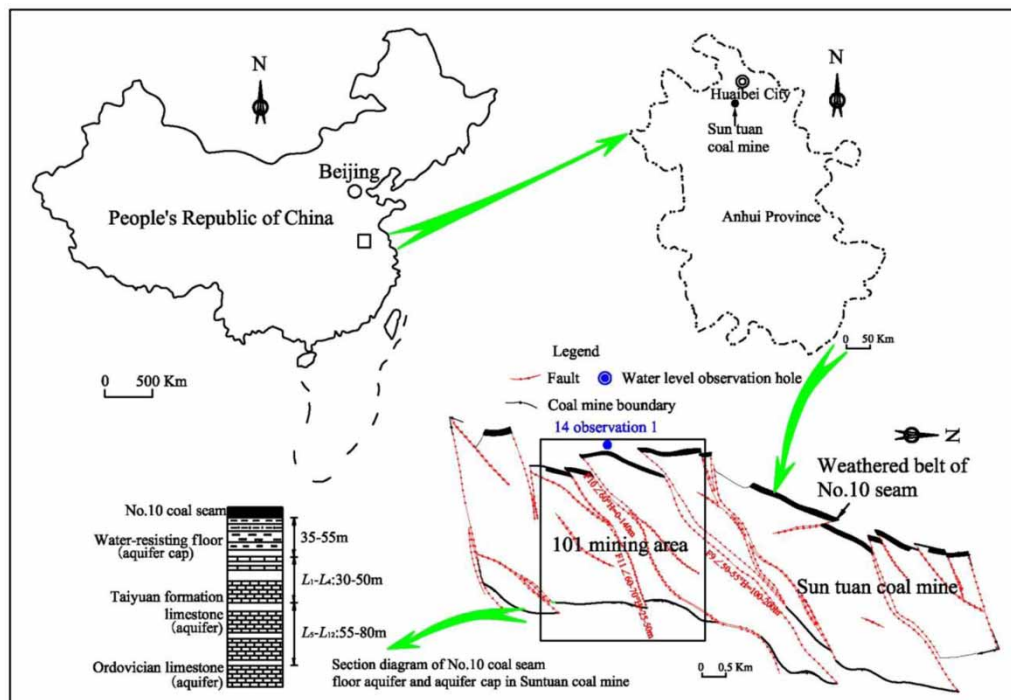


Figure 4 | Study area location.

the total. The limestone's water-bearing horizons L_1 to L_4 are the main factor affecting the No. 10 seam's mining safety. The aquifer below horizon L_4 is far enough from the seam for its impact on mining to be small.

The trend of the mine stratum is approximately north-south, and it dips to the east at about 10° in a monoclinical structure. There are many faults, most of which are tensional and torsional. Little flushing fluid leaks into the fault fracture zone during drilling. Pumping test data from the fault zone show that typical borehole inflow, q , is 0.016 to 0.00,048 L/(s.m), and K is 0.023 to 0.0017 m/d. As the

permeability of the faults is low, the water-bearing upper member of Taiyuan Formation is a closed and weak aquifer, making it feasible to use drainage to lower the head.

During exploration, seven boreholes were drilled to carry out pumping tests on L_1 – L_4 aquifer. The hydrogeological results are shown in Table 1.

Table 1 | L_1 – L_4 aquifer pumping test

Borehole	Aquifer roof elevation H_a (m)	Initial water level elevation H_0 (m)	Inflow q (L/s.m)	Permeability coefficient K (m/d)
22-23-1	–261.2	+19.91	0.058	0.21
27 – 1	–320.59	+21.12	0.055	0.17
07 observation 3	–210.32	+18.39	0.77	2.99
14 observation 1	–205.35	+1.22	1.55	3.93
25-26-S1	–878.13	+14.22	0.0082	0.026
13-14-S4	–565.36	+14.20	0.0052	0.027
11 observation 2	–220.35	+21.1	0.093	0.28

As can be seen, $q = 0.0052$ to 1.55 L/(s.m), and $K = 0.026$ to 3.93 m/d, with plenty of water and good connectivity in the shallow sub-crop, but becoming weaker with increasing depth. The yield, q , and permeability, K , from different boreholes also differ, further illustrating the upper limestone aquifer's heterogeneity.

Working faces 1013 and 1011 are in 101 mining area, which is divided into several blocks by large faults – F9, F10 and F11. The two faces are between F9 and F10 (Figure 4), and their hydrogeological conditions are relatively independent. Beneath the working faces is the Taiyuan Formation aquifer, where the total thickness of L_1 – L_4 is 50 m. Of 126 water exploration boreholes in the upper part of the aquifer (L_1 – L_4) in the mining area, only four yielded more than 5 m³/h, while most were dry. Since mining began in 2007, the Taiyuan Formation limestone has been drained. Prior to mining of the two working faces, the water level in observation borehole 14-observation 1 was -50 m, and the minimum combined coal seam and aquifer thickness was 45 m. The lowest working face elevation was calculated as -515 m, so the maximum head on the base of the aquifer cap was 4.65 MPa, and the water inrush coefficient about 0.103, exceeding the critical value in the 'detailed rules for the prevention and control of water in coal mines' (China State Administration of Coal Mine Safety 2018), so there is danger of water ingress. The plan was to allow 1 year for drainage to lower the head, and the goal was to reduce the head to the critical water inrush coefficient value to ensure mining safety.

Because of the aquifer's drainage characteristics and to ensure the safety of the two working faces, a special drainage roadway was constructed (Figure 5), which directly exposes the limestone. The roadway floor elevation varies from -541.9 to -540.7 m, and it is 390 m long. According to the hydrogeological exploration report, the aquifer thickness (L_1 – L_4) in the mining area is 50 m, K is 0.03 m/d, and μ^* (the storage coefficient) is 1×10^{-6} . The drainage borehole radius, r_w , is 0.05 m, and the maximum single-borehole drawdown, S_{\max} , 490 m.

Optimization model establishment and solution

Water level control points should be at the upper and lower ends of the roadway far from the drainage borehole and the deepest working face – see Figure 2. Control points measure the head at the base of the coal seam's aquifer cap; that is, $z = 0$ and $d = 0$ for the drainage borehole. According to the Huabei mining regulations, the working face critical water inrush coefficient is 0.06 MPa/m, as noted, and the safe water pressure at the control point is 2.7 MPa (from Equation (7)). The safe water levels and drawdowns at the control points can be calculated from this and are shown in Table 2.

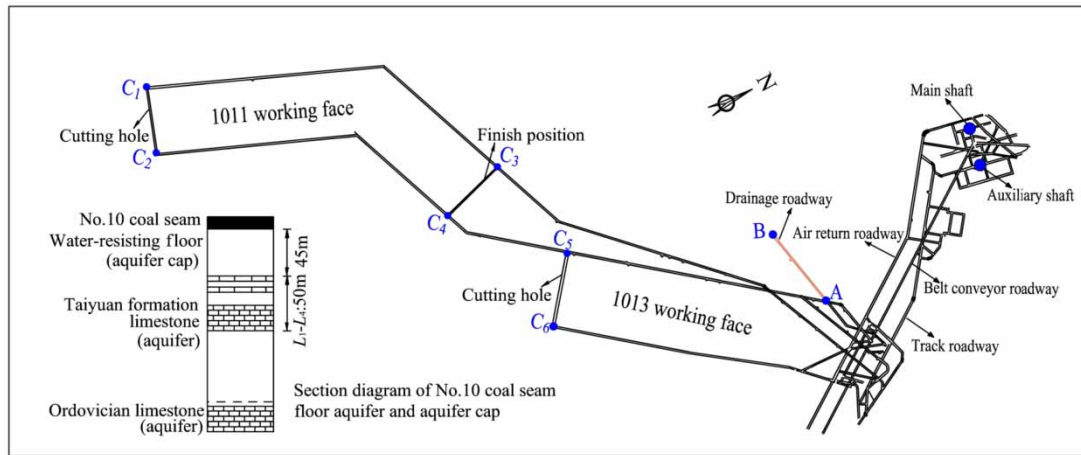


Figure 5 | Working faces and water level control points in the mining area.

Table 2 | Safe drawdowns at water level control points

Control point	x (m)	y (m)	Base of aquifer cap H_0 (m)	Safe head at control point H_s (m)	Safe drawdown at control point S_s (m)
C ₁	360.26	971.06	-360	-90	40
C ₂	381.85	790.39	-390	-120	70
C ₃	1,263.51	774.97	-425	-155	105
C ₄	1,144.15	643.54	-450	-180	130
C ₅	1,427.15	338.74	-540	-270	220
C ₆	1,787.30	269.39	-565	-295	245

The drainage boreholes were drilled along roadway section AB . The coordinates of A and B are (2,008.42,582.83) and (2,146.8,408.48), respectively, and the roadway can be generalized into a linear equation as $y = -1.23x + 3,057.4$ ($2,008.42 \leq x \leq 2,146.8$). The optimization model is solved using the MOPSO algorithm based on Matlab software – the results are shown in Table 3. Taking the incomplete well as an example ($l/M = 0.8$), all calculation results meeting the constraints can be obtained, as shown in Figure 6. That is, n and Q (the total flow $n * Q$ is known, of course). According to the optimization principle (n , Q and $n * Q$ are minimum), the final optimization result is $n = 5$, $Q = 104.9 \text{ m}^3/\text{d}$, and the specific results are shown in the third row of Table 3.

Table 3 | Optimization results

l/M	n	First borehole coordinates x (m)	Spacing D (m)	Yield Q (m^3/d)	Drilling quantities $l \times n$ (m)	Total yield $Q \times n$ (m^3/d)
1 (fully penetrating well)	4	2,012.2	62.17	131.05	200	524.2
0.8 (partially penetrating well)	5	2,008.4	51.23	104.9	200	524.5
0.6 (partially penetrating well)	6	2,008.4	39.02	87.33	180	523.98
0.4 (partially penetrating well)	8	2,036.1	24.76	65.91	160	527.31
0.2 (partially penetrating well)	16	2,034.1	11.69	32.9	160	526.4

Table 3 shows that when the drainage borehole is fully penetrating, the optimal number of drainage boreholes, n , is 4, the spacing between them 62.17 m, the yield from a single borehole $131.05 \text{ m}^3/\text{d}$, and the total yield $524.2 \text{ m}^3/\text{d}$. For partially penetrating boreholes, the amount of

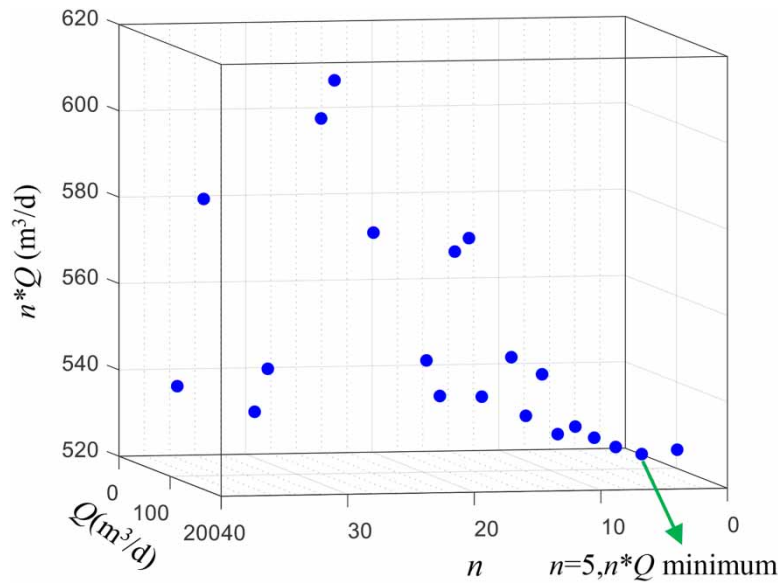


Figure 6 | Solutions for all constraints of a partially penetrating well.

drilling decreases, but more boreholes are needed and the single-borehole yield decreases, and there is little difference in the total yield. However, the total amount of drilling decreases step by step.

It can be seen from the above that, for a low permeability, heterogeneous aquifer, a single, low yield borehole can achieve the drainage required. However, when the yield from a single borehole is low, many are needed and construction costs are high. In this case, the aquifer is a composite of horizons L_1-L_4 . Generally, the yield from L_3-L_4 is the highest. This is because L_3-L_4 accounts for a large proportion of the thickness of L_1-L_4 . If the drilling depth is insufficient, it becomes difficult to penetrate to L_3-L_4 . The optimization calculation results show, however, that when $l/M = 0.6$, the number of boreholes and extent of drilling are moderate, and the total yield is also lowest, which is an ideal design scheme.

Parameters

(1) Aquifer permeability

To determine the influence of aquifer permeability on drainage, when μ^* and K are known, the optimal n and Q are needed – see Figure 7.

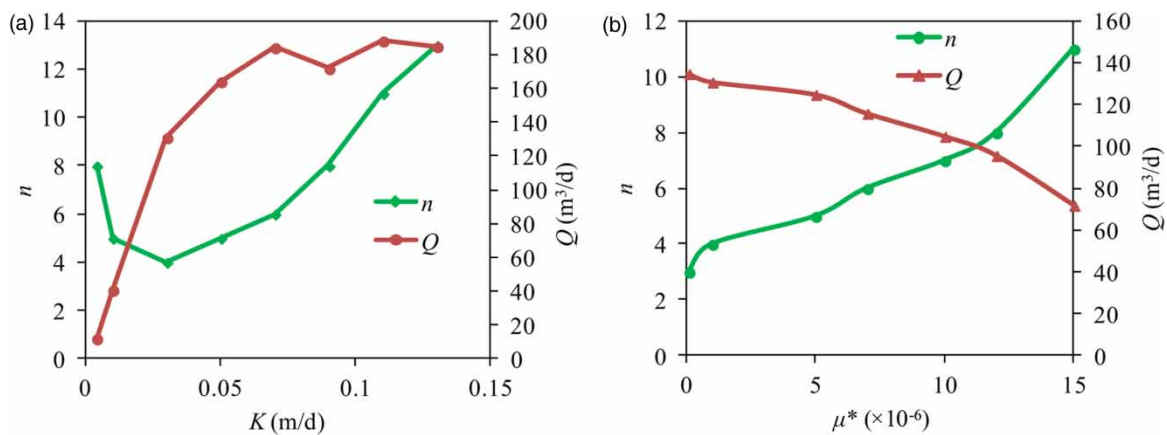


Figure 7 | Influence of hydrogeological parameters on the optimization model: (a) K ; (b) μ^* .

As K increases gradually, n first decreases then rises. It is at its lowest when $K = 0.03$ m/d. This shows that the effect of drainage in low permeability aquifers is better when measures like installing intermediate drainage boreholes and reducing individual borehole yields are taken. In addition, as K increases, borehole yields, Q , generally increase but, above some high K value, increasing n has little effect on Q .

(2) Aquifer storage coefficient

To determine the influence of μ^* on the optimization results, the optimal n and Q are needed – Figure 6. μ^* reflects the aquifer's available water content. So, as μ^* increases, the optimal number of drainage boreholes under the constraint conditions also increases, while the single-borehole yield decreases and the total yield increases.

Drainage effect

In reality, in the mine, the optimization results were noted and the partially penetrating borehole scheme adopted. Individual borehole yields were reduced, the number of drainage boreholes was increased appropriately and other measures were taken to deal with the aquifer drainage problems. In the two roadway drilling fields, six cross limestone layer drainage boreholes were installed (Figure 8). One borehole is in the third limestone horizon, but the other five are all in the horizon L_4 . Individual boreholes yield between 52 and 100 m³/d.

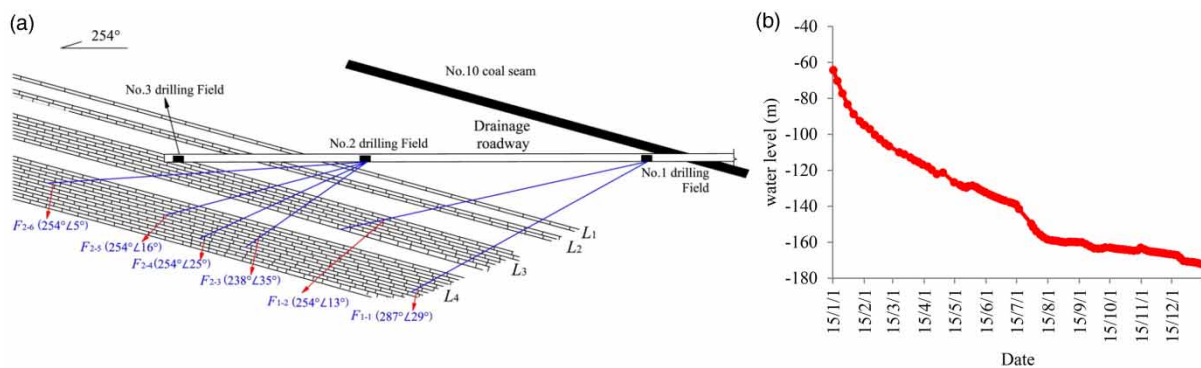


Figure 8 | Layout of drainage works and water level observation boreholes. (a) drainage layout section; (b) water level in 14-observation 1 borehole.

In the drainage roadway, the sub-horizontal drainage boreholes along the limestone layer, which are generally long – it is difficult and expensive to drill in the roadway – combined with the drainage holes penetrating the layer, can achieve better drainage. For this reason, four sub-horizontal drainage boreholes were constructed along the 170°, 196°, 206° and 222° azimuth in the drainage line of No. 3 drilling field. The drainage boreholes are essentially parallel to the trend of horizon L_4 , and their average length is 140 m.

The total discharge in 2015 from the limestone in mining area 101 was about 490,000 m³ at an average yield of about 56 m³/h. The water level in borehole 14 observation 1, which is on the ground outside the mining area, fell from -50 to -170 m – that is, 120 m – Figure 8(b). The maximum daily fall was 2.4 m. The head measured at the working face is 0.2 MPa (corresponding to a water level of -320 m), and the elevation of the lowest point of the working face mining section is -401.1 m, so that the maximum working face water inrush coefficient is 0.026 MPa/m, basically reaching the goal of drainage mining.

For the inclined shafts in the actual project, the conversion method is often used to calculate draw-down, which introduces calculation errors. It is also noted that this model is not suitable for

calculating drawdown in horizontal drainage boreholes or along the limestone horizons. However, the model is of some help in determining individual borehole yield, the degree of borehole penetration into the aquifer and the number of boreholes needed, when applied to the drainage of a low permeability aquifer.

CONCLUDING REMARKS

Based on the aquifer's low permeability, and the requirements of economy and environmental protection, a multi-objective optimization model for multi-borehole drainage was established. The model takes the minimum single-borehole yield and number of boreholes as the objective function, and the drainage borehole and water level control point drawdown as the constraint conditions. The model was applied to a coal mining face in the Huaibei mining area. While ensuring safety in coal mining, the research results protect the groundwater resources to the greatest extent and reduce the amount of drilling required. The main conclusions are as follows:

- (1) When drainage borehole penetration of the aquifer (l/M) is reduced, the number of optimized drainage boreholes, n , increases gradually, but the yield from individual boreholes decreases while the total yield remains about the same. At the same time, the total amount of drilling required decreases step by step. Because this is a low permeability, heterogeneous aquifer, it is better to drain it using larger numbers of partially penetrating boreholes, and reduce the yield of individual boreholes appropriately.
- (2) The hydrogeological parameters affect the optimization results significantly. With increasing K values in the aquifer, the optimum number of drainage boreholes first decreases then increases, while the individual borehole yield, Q , increases before leveling out. As μ^* increases, the optimal number of drainage boreholes increases and the individual borehole yield decreases.
- (3) The upper Taiyuan Formation is a compound aquifer comprising horizons L_1-L_4 , of which L_3 and L_4 have good yields. This suggests that drainage boreholes should penetrate the third limestone horizon (L_3).

ACKNOWLEDGEMENTS

This study was partially supported with research grants from the major projects of natural science research in Higher Education Institutions (KJ2019ZD11) and the National Natural Science Foundation of China (41977253). The data used in this paper can be accessed by contacting the corresponding author directly.

REFERENCES

- Chen, L. W., Liu, J. L. & Gui, H. R. 2012 Numerical simulation of evolution of potential water inrush area in coal seam floor on the top of high-confined aquifer. *China Mining Magazine* **21**(3), 81–84.
- China State Administration of Coal Mine Safety. 2018 *Detailed Rules for the Prevention and Control of Water in Coal Mines*. Coal Industry Press, Beijing, China.
- Coello, C. A. C. & Lechuga, M. S. 2002 MOPSO: a proposal for multiple objective particle swarm optimization. In *IEEE Congress on Evolutionary Computation*, Piscataway, New Jersey, pp. 1051–1056.
- Dolatshahi-Zand, A. & Khalili-Damghani, K. 2015 Design of SCADA water resource management control center by a bi-objective redundancy allocation problem and particle swarm optimization. *Reliability Engineering & System Safety* **133**, 11–21.
- Guo, W. J. & Liu, Y. X. 1989 The concept of water inrush coefficient and its application. *Hebei Coal* **2**, 56–60.
- Kostecki, T. & Spearing, A. J. S. 2015 Influence of backfill on coal pillar strength and floor bearing capacity in weak floor conditions in the Illinois Basin. *International Journal of Rock Mechanics and Mining Sciences* **76**, 55–67.

- Li, B. Y. 1999 'Down three zones' in the prediction of water inrush from coalbed floor aquifer-theory, development and application. *Journal of Shandong Institute of Mining and Technology* **18**(4), 11–18.
- Li, W., Liu, Y., Qiao, W., Zhao, C., Yang, D. & Guo, Q. 2018 An improved vulnerability assessment model for floor water bursting from a confined aquifer based on the water inrush coefficient method. *Mine Water and the Environment* **37**(1), 196–204.
- Lu, H. F., Yao, D. X., Shen, D. & Cao, J. Y. 2015 Fracture mechanics solution of confined water progressive intrusion height of mining fracture floor. *International Journal of Mining Science and Technology* **2015**(1), 99–106.
- Lu, H., Liang, X., Shan, N. & Zhang, Y. K. 2018 Study on the stability of the coal seam floor above a confined aquifer using the structural system reliability method. *Geofluids* **2018**, 1–15.
- Meng, L., Feng, Q. Y. & Ding, E. J. 2015 Optimization method for single borehole drainage of high pressure water well in coal seam floor. Chinese invention patent: 201510354956.6201506.
- Qian, M. G., Miao, X. X. & Li, L. J. 1995 Mechanical behavior of main floor for water inrush in longwall mining. *Journal of China University of Mining & Technology* **5**(1), 9–16.
- Qian, M. G., Miao, X. X., Xu, J. L. & Mao, X. B. 2003 *Key Strata Theory in Ground Control*. China University of Mining and Technology Press, Xuzhou.
- Song, P. Z., Wang, J. Y. & Liu, W. 2016 Water resource security evaluation model based on PSO optimization logic STI curve. *Journal of Natural Resources* **31**(5), 886–892.
- Sulis, A., Buscarinu, P. & Sechi, G. M. 2011 Using reservoir trophic-state indexes in optimization modeling of water-resource systems. *Environmental Modelling & Software* **26**(6), 731–738.
- Sun, J., Wang, L. G. & Hou, H. Q. 2012 Application of microseismic monitoring technology in mining engineering. *International Journal of Mining Science and Technology* **22**(1), 79–83.
- Wang, J. M., Ge, J. D. & Wu, Y. H. 1996 Mechanism on progressive intrusion of pressure water under coal seams into protective aquiclude and its application in prediction of water invasion. *Journal of Coal Science & Engineering* **2**(2), 9–15.
- Wang, C. L., Liu, J. L. & Gui, H. R. 2012a Numerical simulation of dynamic evolution of potential water inrush area of mining coal seam floor on high pressure water body. *China Mining* **21**(3), 81–84.
- Wang, Z. R., Luo, B. L. & Niu, Y. G. 2012b Research and application of decision-making visualization system for optimal allocation of water resources in Dalian. *Journal of Dalian University of Technology* **52**(2), 259–263.
- Wu, Q., Fan, Z. L., Zhang, Z. W. & Zhou, W. F. 2014 Evaluation and zoning of groundwater hazards in Pingshuo No. 1 underground coal mine, Shanxi Province, China. *Hydrogeology Journal* **22**(7), 1693–1705.
- Wu, Q., Guo, X. M., Shen, J. J., Xu, S., Liu, S. Q. & Zeng, Y. F. 2017 Risk assessment of water inrush from aquifers underlying the Gushuyuan coal mine, China. *Mine Water and the Environment* **36**(1), 96–103.
- Yin, H., Lefticariu, L., Wei, J., Guo, J., Li, Z. & Guan, Y. 2016 In situ dynamic monitoring of stress revolution with time and space under coal seam floor during longwall mining. *Environment and Earth Science* **75**(18), 1249.
- Yuan, L. 2019 Scientific problem and countermeasure for precision mining of coal and associated resources. *Journal of China Coal Society* **44**(1), 1–9.
- Zhang, J. C. 2005 Investigations of water inrushes from aquifers under coal seams. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts* **42**, 350–360.
- Zhao, X. Q. & He, Z. A. 2015 Water resources optimal scheduling based on improved chaos genetic algorithm. *Journal of Lanzhou University of Technology* **41**(4), 65–70.
- Zheng, S. T. 2018 Advanced exploration and treatment technology of limestone water damage area in coal seam floor of Lianghuai coalfield. *Coalfield Geology and Exploration* **46**(4), 142–146.