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ORIGINAL ARTICLE

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Management of karst water resources in mining area: dewatering in mines and demand for water supply in the Dongshan Mine of Taiyuan, Shanxi Province, North China

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Abstract Coalfields in North China contain six to seven coal seams in the Permo-Carboniferous strata. The coal seams are underlain by the Ordovician limestone. Large-scale dewatering or depressurizing of the karst aquifer was considered essential to avoid water inrushes and keep the mines safely operational. This practice, however, has caused water supply shortage in the mining areas. The most effective solution to this conflict is to use the uncontaminated karst water from the mines for water supply. This paper explores a management model to maximize the utilization of the karst water while maintaining the safe operation of the mines. The model can provide essential information on water resource distribution for decision makers. The model was applied to the Dongshan Coal Mine in Taiyuan City, China.

Keywords Water resources · Karst · Management model · Mine dewatering · China

Introduction

Coal seams in the coalfields of North China lie in the Permo-Carboniferous strata, which are underlain by the Ordovician limestone. The Ordovician limestone is strongly karstified and highly permeable. Most of the karst aquifer is confined, and the average thickness of the aquifer is 650 m. Due to the potential impacts of the confined water in the Ordovician limestone on the mining activities, large-scale dewatering or depressurizing of the aquifer was considered essential to avoid water inrushes and to keep the mines safely operational. Groundwater in the karst aquifer is also a valuable natural resource for local people. Dewatering in the coal mines has caused water supply shortage in the mining areas.

In the Dongshan Mine of Taiyuan, China, the main coal seam is in the Taiyuan Formation and the bottom of the coal seam has elevations ranging from 300 to 700 m above the mean sea level (amsl). The potentiometric pressure of the underlying Ordovician limestone varies from 786 to 800 m amsl, which is several hundred meters higher than the coal seam. In some areas, such as the northwestern corner of the mine, the elevation difference between the potentiometric pressure and the coal seam creates hydraulic pressures up to 56.7 kg/cm^2 against the coal seam. When the coal is mined by the longwall method, an empty space is formed. The floor of the empty area is vulnerable to fracturing under the water pressure from the Ordovician limestone. The karst water inflow into the opening may flood the mine. Thus, depressurizing of the karst aquifer is necessary to extract the coal. However, dewatering in the mine reduces the amount of water available for supply in the area. On the other hand, preservation of the water resources for the supply undermines the mining industry of the area. This dilemma can only be resolved by coordinating the dewatering activity with the demand for water supply.

Site geology

The Dongshan Mine lies in the east of Taiyuan City, Shanxi Province. It covers an area of 1,736 km^2. Topographically, the study site belongs to a mid-low mountain range with higher surface elevations in the northeast and lower elevations in the southwest (Fig. 1). The rainfall is concentrated in July, August, and September of each year. The annual average precipitation is approximately 440 mm, with a range from 217 mm (1972) to 749 mm (1969). The annual average evaporation is approximately 1,849 mm.

Hydrologically, the study area is in the Fenhe watershed, which is affiliated to the Yellow River basin. Two tributaries of the Fenhe—Yangxinghe and Nidunhe—flow through the site, and their discharges vary with seasons.

Rock formations consist of (1) metamorphic rock in the Wutai Formation of the Archean Group and in the Hutuo Formation of the Proterozoic group; (2) Cambrian and Ordovician limestone; (3) coal-bearing strata of Carboniferous and Permian sandstone, limestone, and shale; and (4) unconsolidated materials of the upper tertiary and quaternary systems.

There are three tectonic belts trending EW, SN and NE in the study area (Fig. 2). Each tectonic belt consists of multiple geologic structures, as listed below.

- EW tectonic belt: Sangei horst, Yangqu tectonic structure, Donglingjing fault, Guanjiayu fracture, Shilingguan tectonic structure, and Mapo fracture.
- SN tectonic belt: Qizishan horst, Dongshan fracture, and Fanzhuang fracture.
- NE tectonic belt: Dongshan anticline, Beixingdao fault, Hujiawa fault, and Beizhuanjing–Dujiashan fault.

Precipitation is the major recharge source to the Dongshan karst groundwater system. The groundwater flows from north to south and from northeast to southwest. The lateral discharge of the groundwater system and artificial exploitation are the two major forms of discharge. Lateral discharge occurs naturally

Fig. 1 Geographic location of the Dongshan Coal Mine

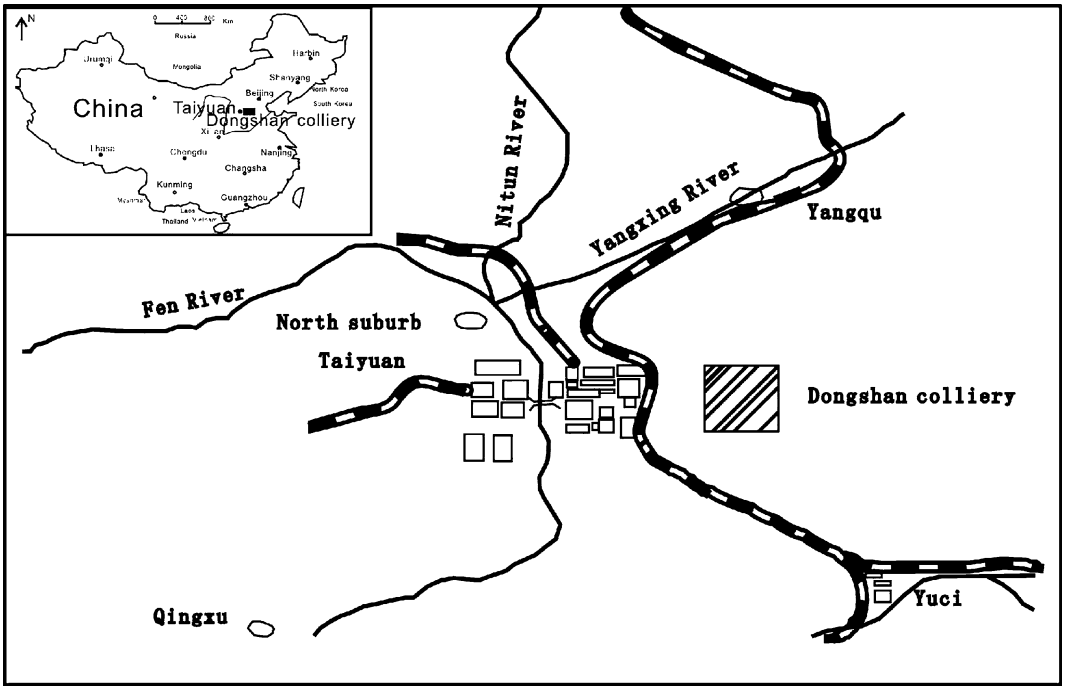
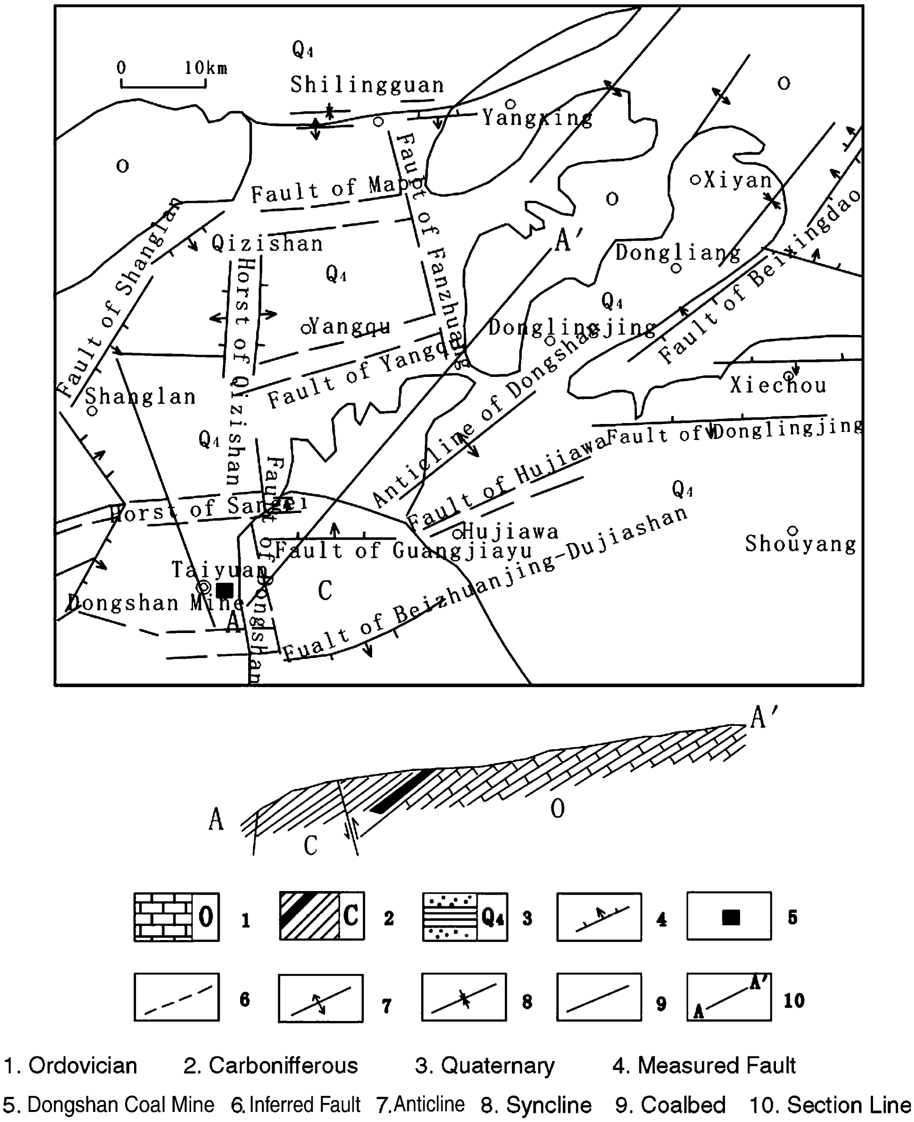


Fig. 2 Geologic structures in the Dongshan Mine, Taiyuan



and is controlled by the geologic structures. Field data have supported the following lateral discharges:

- From south of the Qizishan horst and Sangei horst to Lancunquan;
- From the slightly permeable boundary of the southern border of the Sangei horst to basin;
- From the eastern Hangling to the slightly permeable boundary of Daweishan;
- Flows through the permeable boundary in the complex part of the Guanjayu fracture belt with EW trending and Dongshan anticline.

Artificial exploitation includes two major water fields—Zaogou and Guanmengqian—individual wells, and dewatering in the Dongshan Mine.

Conceptual site model

Aquifer characteristics

The aquifer system of interest is in the Cambrian and Ordovician carbonate rocks. The aquifer is unconfined in the area where the rocks are exposed on the surface, and confined in the area where the rocks are overlain by impermeable strata. The lithology, structure, and permeability of the aquifer control the karst development. The aquifer is heterogeneous, and its heterogeneity is represented by the permeability and porosity of the aquifer.

Because the horizontal scale in the karst aquifer is much larger than the vertical scale, the vertical flow component of the aquifer can be reasonably ignored for the water resource evaluation. The aquifer was treated as a two-dimensional seepage medium.

Boundary conditions

The boundary conditions are mainly controlled by geologic structures. Figure 5 shows the boundary conditions for the study area.

1. The northwestern boundary can be divided into the eastern and western sections.
   - Eastern section: the eastern section is further divided into the northern and northwestern parts. The northern part of the eastern section is the Xizhoushan structural belt with NE strike, while the northwestern part of the eastern section is associated with impermeable granite.
   - Western section: this section is at the Shilingguan structural belt with EW strike. Basal shale consists of the impermeable boundary in the north. In general, the northwestern boundary is impermeable.
2. The northeastern boundary is the divide of the regional watersheds with zero flow. The boundary can be divided into four sections from NE to SW.
   - Section 1 lies along the Beixindao–Sijiaping faulted zone. It is an impermeable boundary made of the pre-Cambrian basal argillutite and intrusive dyke.
   - Section 2 lies between the Beixingdao fault and Dongshan anticline and consists of lower Cambrian limestone. It is a secondary boundary with low transmissibility.
   - Section 3 lies along the Dongshan anticline and Guojiazhuang fault. Because the anticline axle and fault are watertight, this section is impermeable.
   - Section 4 lies along the fault south of the Dongshan anticline. The rocks are fractured, and the boundary is permeable.
3. The western boundary is divided into three sections.
   - Northern section: This lies in the structural line with SN strike in the Qizishan horst. The fault displacement is more than 600 m. Cambrian shale has contact with the limestone on both sides. Therefore, this boundary is impermeable.
   - Middle section: This ranges from the southern tip of the Qizishan horst in the north to the northern border of the Sangei horst in the south. It is dissected by the fault with NE trend and becomes the diversion passage. This section belongs to a diversion boundary.
   - Southern section: The southern section lies in the Beizhuanjing–Dujiashan faulted zone. The lithology on both sides is complex due to faulting. It belongs to a weakly permeable boundary.

Sources and sinks

Recharge from atmospheric precipitation

The outcrops of the carbonate rocks and the area mantled by thin soil receive recharge from rainfalls. Because the vadose zone in the Dongshan karst area is thick, not all the precipitation reaches the groundwater. When the monthly rainfall is less than 20 mm, the effective recharge to the groundwater would be zero.

Groundwater pumping

Exploitation of groundwater through pumping is extensive in the study area. Two major well fields—Zaogou and Guanmengqian—are present, in addition to some sporadic pumping and mine dewatering. In the numerica modeling, the pumping wells were arranged at the nodes.

Stream seepage

The surface streams are seasonal. The recharge from the surface water was considered with the precipitation.

Mathematical model and calibration

The groundwater flow in the karst aquifer is mathematically described by:

$$\frac{\partial}{\partial x}\left(T\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial H}{\partial y}\right)+\omega-\sum_{j}Q_j\delta(x-x_{wj},y-y_{wj})$$

$$=\mu\frac{\partial H}{\partial t}\quad (x,y)\in G,t>0$$

$$H(x,y,t)=H_0(x,y)\quad (x,y)\in G,t=0$$

$$T\frac{\partial H}{\partial n}=q(x,y,t)\quad (x,y)\in\Gamma_2,t>0,$$

where

H	water level or potentiometric pressure of the aquifer;
H_0	initial water level of the aquifer prior to modeling;
T	transmissibility;
μ	specific yield for the unconfined part of the aquifer, and the coefficient of storage for the confined part of the aquifer;
q	flow rate through the secondary boundary;
ω	recharge intensity of rainfall;
Q	pumping rate in wells;
n	normal to the boundary;

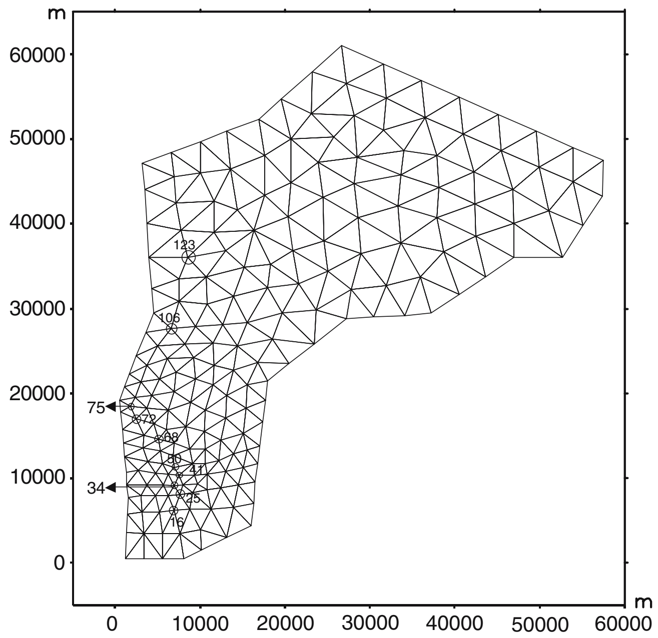


Fig. 3 Finite-difference discretization of the study area

G computing area; and
Γ_2 secondary boundary.

The finite-difference method in the triangular grid was used to solve the above equation. The area was divided into 358 units with 210 nodes (Fig. 3). Because most of the hydrogeological data are available monthly, the time step was one month in the modeling.

The data collected from February 1992 to January 1994 was used to calibrate the model. During this period, the hydrogeological data were relatively complete. The flow field in February 1992 was used as the initial state. The flow field of January 1994 was used for a comparison with the observation data in six monitoring wells. Figure 4 provides the results from the modeling with those measured in the wells. The water level contour map is shown in Fig. 5.

The model calibration process resulted in the values for transmissibility (T) and storativity (μ). Table 1 gives the results and the associated heterogeneous regions are shown in Fig. 6.

Numerical model for water resource management

Objective function

The high groundwater pressure in the Ordovician limestone threatens the safe operations in the Dongshan Mine as water inrushes or mine flooding can occur if the pressure is not significantly reduced. Dewatering is a necessity to mine the coal. Large-scale dewatering, however, may also cause adverse impacts on the environment. To properly manage the water resources in the karst aquifer, the objectives that are to be accomplished include (Wu and Jin 1995):

- Minimizing the dewatering effort in the mine while maintaining its safe operation; and
- Maximizing the amount of water available for water supply. Three discharge points are designed to lower the groundwater level uniformly, and they are in the south, central, and north parts of the district, respectively. The three designed discharge points are at nodes 25, 50, and 68 in the management model. The other sources that extract water from the same aquifer are Zaogou and Menguanqian well fields, and the water already flowing to the mine.

In the next 20 years, two managing periods are planned, each lasting 10 years. The first 10 years is the No. 1 period and the second 10 years forms the No. 2 period. There are 12 decision-making variants. The objective functions are described by:

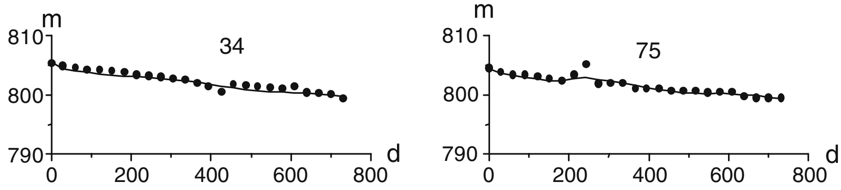
$$\mathrm{Min}Z_1 = \sum_{i=1}^{N_1} \sum_{j=1}^{M} C(i,j)\, Q(i,j)$$

$$\mathrm{Max}Z_2 = \sum_{i=1}^{N_2} \sum_{j=1}^{M} C(i,j)\, Q(i,j),$$

where

$C\ (i, j)$ coefficients related to cost, this factor was not considered in this study;
$Q\ (i, j)$ decision-making variants (1,000 m^3/day);
N_1 number of discharge points for advance dewatering, $N_1 = 3$;
N_2 number of existing sources that take water from the aquifer, $N_2 = 3$;

Fig. 4 Water level comparison at monitoring wells



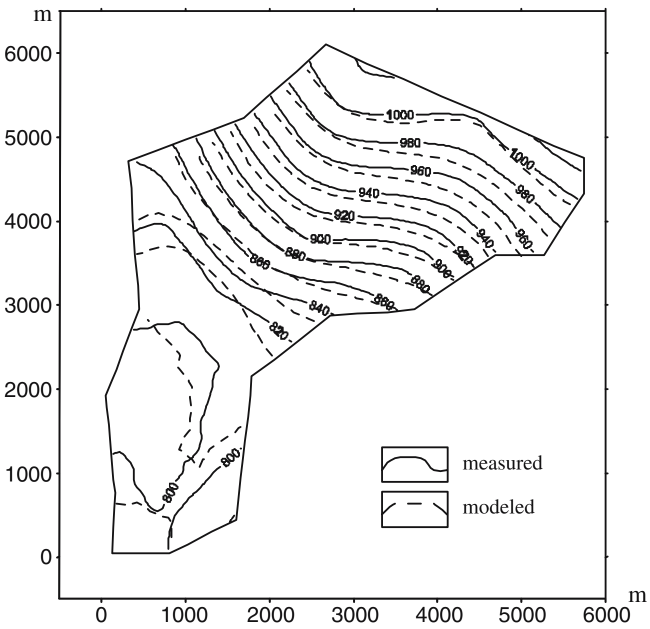


Fig. 5 Contour maps from the modeled and measured groundwater levels

M	are the managing periods, $M = 2$;
Z_1	is the amount of water from the advance dewatering effort; and
Z_2	is the amount of water available for supply.

Restrictions

The purpose of advance dewatering is to lower the groundwater level in the Ordovician limestone and ensure that water inrushes do not occur. Seven nodes were selected inside the working area to represent the required groundwater level. These nodes are 25, 50, 68, 24, 33, 49, and 59. The restriction on the groundwater level is expressed by:

$$\sum_{i=1}^{N} \beta\,(k,i,2)\,Q(i,1) + \sum_{i=1}^{N} \beta\,(k,i,1)\,Q(i,2) + S_0(k) \\ \geq B(k),$$

where

$\beta(k,\ i,\ j)$	response function of unit impulse;
$Q\ (i,\ j)$	decision-making variants (1000 m^3/day);
$S_o\ (k)$	additional drawdown of point K;
$B\ (k)$	most permissible drawdown of point K by the end of the planning term;
N	number of sources that extract water from the karst aquifer ($N = N_1 + N_2$), $N = 6$; and
K	is the number of restricted points, $K = 7$.

The pumping rates for all the sources are non-negative, i.e.,

$$Q(i,j) \geq 0.$$

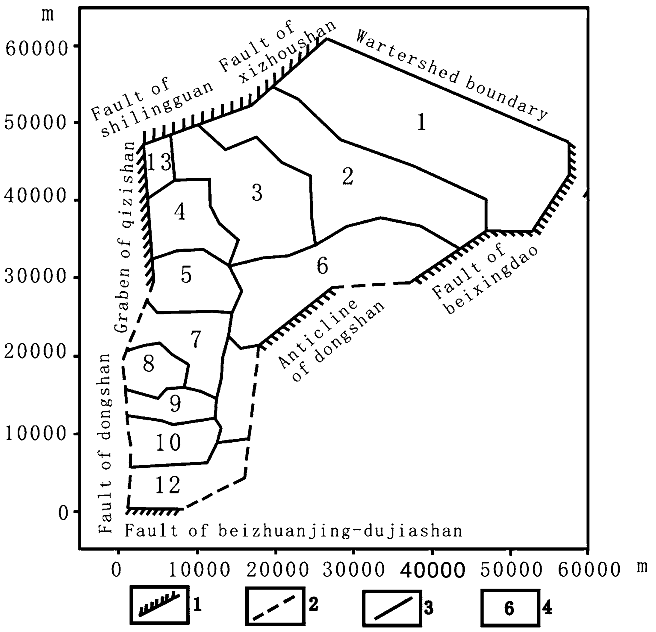
Philip multi-objective simplex method

Two objective functions are involved in the management model. The traditional method is to fix the weight number in anticipation, and to combine multiple objects into an individual one. When the individual objective function reaches the maximum value, a non-inferior solution is obtained. In this study, the Philip multi-objective simplex method algorithm is used to solve the problem. This method reverses the traditional calculation processes and has been well documented (Chen et al.1991; Shao et al. 1998; Datta et al. 1986; Bogardi et al. 1991; Magnouni and Treichel 1994). Figure 7 shows the flowchart to obtain the non-inferior solution using the Philip Algorithm (Wang 1991). The following are the specific steps.

1. Find a feasible solution.
2. Is the current solution obviously non-inferior?
3. Is the current solution obviously inferior?
4. Is the current solution non-inferior by a less obvious manner?
5. Is one search direction obviously better than all others?
6. Do any of the research directions lead to a change in the objectives?
7. Find an unexplored basis with a new non-basic variable in storage.
8. Would the introduction of a non-basic variable lead to an unexplored basis?

Table 1 Hydraulic parameters for the Ordovician limestone aquifer

Zone no.	Transmissibility T (m^2/day)	Storativity μ	Zone no.	Transmissivity T (m^2/day)	Storativity μ
1	250	0.03	8	15,000	0.0004
2	300	0.025	9	8,500	0.0003
3	200	0.005	10	10,000	0.0003
4	300	0.005	11	1,500	0.00025
5	2,000	0.025	12	300	0.00035
6	500	0.045	13	3,000	0.025
7	5,500	0.00045			



1.Tectonic impermeable boundary; 2.Permeable and slightly permeable boundary; 3.Watershed impermeable boundary; 4.Number of heterogeneous region.

Fig. 6 Heterogeneity of the study area and boundary conditions

9. Introduce a non-basic variable and remove a basic variable to form a new basis.

Simulation results

With the help of the Philip method discussed above, the model can simulate different options of the water resource distribution. Table 2 provides the results for one scenario in which:

- The groundwater level is to be lowered to 760 m amsl in 20 years;
- The amount of water already flowing into the mine is 0.4×10^4 m^3/day and remains unchanged for the simulated 20 years;
- The pumping rates at the Zaogou well field is 7.5×10^4 m^3/day and remains unchanged for the simulated 20 years;
- The pumping rates of the three designed advanced dewatering wells are 0.4×10^3, and 0 m^3/day and these remain unchanged in the 20 years;
- the pumping rate at the Guanmengqian well field is 1.5×10^4 m^3/day for the first 10 years and 6.5×10^4 m^3/day for the second 10 years.

Optimal distribution of water resources

Four entities in the Dongshang mining district are to share the karst water resource: the Guanmengqian well field, Zaogou well field, water inflow into the mine, and designed dewatering to lower the water level. The water from the advance dewatering is of excellent quality. All the chemical constituents meet the national standard for drinking water, except bacteria. The water can be used for either domestic or industrial use after a routine treatment. Based on the calculation from the management model, the Guanmengqian well field, the Zaogou well field, the water inflow into the mine, and the designed dewatering can pump 6.5×10^4, 7.5×10^4, 6×10^3, and 4×10^3 m^3/day, respectively, in the second 10 years. The main water users in the study area are a railway bureau, a power plant and the mine itself. It is estimated that the amounts of water consumed from the above institutions are 1.5×10^4 m^3/day by the railway bureau, 5×10^3 m^3/day by the power plant, and 5×10^3 m^3/day by the mine in the second 10 years. The extra amount of water, if any, supplies the Taiyuan city, although the city has its own water supply sources. Let:

- Q_1, Q_2, Q_3, and Q_4 represent the amounts of water from the Guanmengqian well field to the railway bureau, the power plant, the mine, and the Taiyuan city, with the corresponding benefit coefficients of C_1, C_2, C_3, and C_4, respectively;
- Q_5, Q_6, Q_7, and Q_8 represent the amounts of water from the Zaogou well field to the railway bureau, the power plant, the mine, and the Taiyuan city, with the benefit coefficients of C_5, C_6, C_7, and C_8, respectively;
- Q_9, Q_{10}, Q_{11}, and Q_{12} represent the amounts of water from the existing water inflow into the mine to the railway bureau, the power plant, the mine, and the Taiyuan city, with the benefit coefficients of C_9, C_{10}, C_{11}, and C_{12}, respectively;
- Q_{13}, Q_{14}, Q_{15}, and Q_{16} represent the amounts of water from the advanced dewatering to the railway bureau, the power plant, the mine, and the Taiyuan city, with the benefit coefficients of C_{13}, C_{14}, C_{15}, and C_{16}, respectively. The objective is to maximize the benefit acquired from the utilization of water resources, i.e.:

$$\max F = \sum_{i=1}^{16} C_i Q_i.$$

The restricted conditions include the following.

- The supply amount of water cannot surpass the maximum provided by each source, so we have:

$$Q_1 + Q_2 + Q_3 + Q_4 \leq 6.5 \times 10^4\, \mathrm{m}^3/\mathrm{day}$$

$$Q_5 + Q_6 + Q_7 + Q_8 \leq 7.5 \times 10^4\, \mathrm{m}^3/\mathrm{day}$$

$$Q_9 + Q_{10} + Q_{11} + Q_{12} \leq 6 \times 10^3\, \mathrm{m}^3/\mathrm{day}$$

$$Q_{13} + Q_{14} + Q_{15} + Q_{16} \leq 4 \times 10^3\, \mathrm{m}^3/\mathrm{day}.$$

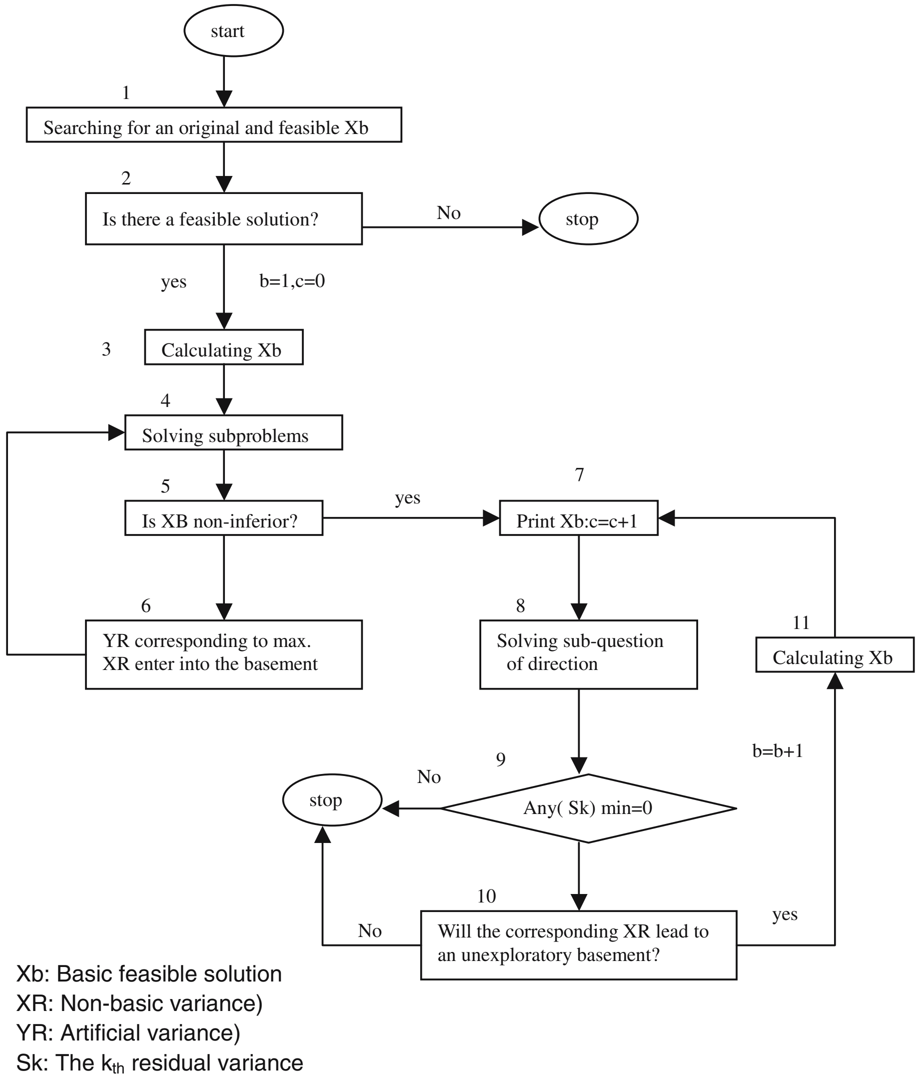


Fig. 7 Flowchart for the Philip multiple objective simplex method

Table 2 Pumping rates at different locations in the Ordovician limestone

No.	1	2	3	4	5	6
Location	Guanmengqian well field	Zaogou well field	Water inflow into mine	S	Central	N
First 10 year	*Q*(1,1)	*Q*(1,2)	*Q*(1,3)	*Q*(1,4)	*Q*(1,5)	*Q*(1,6)
Pumping rate ($\times 10^3$ m^3/day)	15.0	75.0	6.0	0.0	4.0	0.0
Second 10 year	*Q*(2,1)	*Q*(2,2)	*Q*(2,3)	*Q*(2,4)	*Q*(2,5)	*Q*(2,6)
Pumping rate ($\times 10^3$ m^3/day)	60.0	75.0	6.0	0.0	4.0	0.0

S South of mine, *Central* central of mine, *N* north of mine

- The total amount of water supplied to each consumer should be no less than the water demand from each consumer. The amount of water supplied to the Taiyuan city is not restricted but should be as much as possible.

$$Q_1 + Q_5 + Q_9 + Q_{13} \geq 1.5 \times 10^4\,\mathrm{m}^3/\mathrm{day}$$

$$Q_2 + Q_6 + Q_{10} + Q_{14} \geq 5 \times 10^3\,\mathrm{m}^3/\mathrm{day}$$

$$Q_3 + Q_7 + Q_{11} + Q_{15} \geq 5 \times 10^3\,\mathrm{m}^3/\mathrm{day}.$$

- The amount supplied to each consumer by all the sources should not surpass the consumption of water for each consumer. Q_4, Q_8, Q_{12}, and Q_{16} are the amounts of water to the Taiyuan city and do not have the upper limit restrictions.

$$Q_1 + Q_5 + Q_9 + Q_{13} \leq 1.5 \times 10^4 \text{ m}^3/\text{day}$$

$$Q_2 + Q_6 + Q_{10} + Q_{14} \leq 5 \times 10^3 \text{ m}^3/\text{day}$$

$$Q_3 + Q_7 + Q_{11} + Q_{15} \leq 5 \times 10^3 \text{ m}^3/\text{day}.$$

- Non-negative restriction of each variant

$$Q_i \geq 0 \quad i = 1, 2, \ldots, 16.$$

Beneficial coefficient in water resource distribution: fuzzy analysis

Construction of judging matrix

Water quality and the requirements of consumers are important factors affecting distribution of water resources. Relatively speaking, the water quality is more important to domestic uses than industrial uses. Therefore, the index of importance is higher for domestic water and lower for industrial water. On the other hand, it is more reasonable to use poor quality water for industries than drinking. Therefore, for poor quality water, the index of importance is higher for industrial use and lower for domestic use. The scales of index proposed by Satty (He 1997; Xu 2000; Du 2000) were adopted to construct the matrix. Table 3 gives the definition of the scales.

Consistency of the judging matrix

In accordance with the theory of positive matrix, the matrix has a sole and maximum characteristic non-zero value $\lambda_{\max}$. $\lambda_{\max} = n$ if matrix A possesses the following characteristics (assume $a_{ij} = w_i/w_j$):

1. $a_{ii} = 1$
2. $a_{ij} = 1/a_{ji}$ $(i, j = 1, 2, \ldots, n)$
3. $a_{ij} = a_{ik}/a_{jk}$ $(i, j = 1, 2, \ldots, n)$.

Table 3 Definition of scales (He 1997)

Scale a_{ij}	Definition
1	Factor i is as important as factor J
3	Factor i is as slight important as factor j
5	Factor i is more important than factor j
7	Factor i is much more important than factor j
9	Factor i is the most important than factor j
2, 4, 6, 8	Values of scale corresponding to the middle state between the above two judgments
Reciprocal	If factor j is compared with factor i, the judging values obtained are: $a_{ji} = 1/a_{ij}, a_{ii} = 1$

The index of consistence for testing the judgment matrix is:

$$\text{C.I} = \frac{\lambda_{\max} - n}{n - 1} = \frac{-\sum_{i \neq \max} \lambda_i}{n - 1}.$$

Large values of C.I indicate poor consistence of the matrix. When $\lambda_{\max} = n$, C.I = 0, which is completely identical. In general, the consistence of the matrix can be accepted when C.I ≤ 0.1.

The larger the dimension of the matrix n, the worse the consistence of judgment will be. The requirements of consistence for the matrix with high dimension can be relaxed by introducing an adjustment factor (R.I). Table 4 lists the recommended R.I. The consistence of the matrix is thus represented by C.R, in which

$$\text{C.R} = \frac{\text{C.I}}{\text{R.I}}.$$

The maximum characteristic value and the vector of the judging matrix can be solved by the Fussy method and the specific steps are (Qian 1990) the following.

1. Calculate the geometric average of all elements in each line of the matrix to obtain the solution of $\varpi = (\varpi_1, \varpi_2, \ldots, \varpi_n)$

$$\varpi_i = \sqrt[n]{a_{1j} a_{2j} \ldots a_{nj}}.$$

2. Standardize ω to get $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ where

$$\omega_i = \frac{\varpi_i}{\sum_{j=1}^{n} \varpi_j} \quad i = 1, 2, \ldots, n.$$

The results are the evaluated characteristic vector, and they are also the relative weights of all factors.

Table 4 Revised values

Dimensions	1	2	3	4	5	6	7	8	9
R.I.	0.00	0.00	0.58	0.96	1.12	1.24	1.32	1.41	1.45

R.I Adjustment factor

Table 5 Calculated C.R

Matrixes	A_1	A_2	A_3	A_4	A_5	A_6
C.R	0.0043	0.043	0.043	0.05	0.05	0.04

A_1 Judging matrix 1, A_2 judging matrix 2, A_3 judging matrix 3, A_4 judging matrix 4, A_5 judging matrix 5, A_6 judging matrix 6

Table 6 Coefficients of benefit

Coefficient of benefit	Value coefficient	Coefficient of benefit	Value coefficient	Coefficient of benefit	Value coefficient
C_1	0.615	C_7	0.054	C_{13}	0.121
C_2	0.188	C_8	0.548	C_{14}	0.232
C_3	0.127	C_9	0.203	C_{15}	0.581
C_4	0.070	C_{10}	0.578	C_{16}	0.066
C_5	0.256	C_{11}	0.163		
C_6	0.142	C_{12}	0.056		

Table 7 Distribution of water resources (m^3/day)

	Guanmengqian well field	Zaogou well field	Inflow into mine	Dewatering	Total
Railway station	15,000	0	0	0	15,000
Power plant	0	0	5,000	0	5,000
Coal mine	0	0	1,000	4,000	5,000
Taiyuan city	50,000	75,000	0	0	125,000
Total	65,000	75,000	6,000	4,000	150,000

3. Calculate the maximum characteristic value of the matrix,

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A\varpi)_i}{n\varpi_i}$$

where $(A\omega)_i$ is the element i of vector Aω.

4. Calculate the index C.I or C.R and test its consistence. The matrix should be improved to meet the consistent requirement. Table 5 lists the calculation results for C.R. Because all values of C.R are less than 0.1, the matrix meets the requirements of consistence.

The expression $\omega=(\omega_1,\omega_2,\ldots, \omega_n)^T$ is the corresponding beneficial coefficient. Table 6 gives the calculated results.

Optimum solution

Substituting the coefficients into the optimization model and using the simplex method, we obtained the optimum distribution of the water resource (Table 7). From the Guanmengqian well field, 1.5×10^4 m^3/day of water is sent to the railway bureau and 5×10^3 m^3/day to the Taiyuan city. From the Zaogou well field, 7.5×10^4 m^3/day of water is sent to the Taiyuan city. From the existing inflow, 5×10^3 m^3/day of water is sent to the power plant, and 1×10^3 m^3/day to the coal mine district. Approximately 4×10^3 m^3/day is sent to the mine district from advanced dewatering.

Conclusions

1. The dilemma between mine dewatering and water supply is common in the mining areas of North China. Coordination of mine drainage with water supply is probably the most effective approach to solving the problem.
2. The water resource management model was established from the simulation model. It provided the pumping rate for each source, in which water from the Ordovician limestone is extracted to depressurize the aquifer so that the coal can be mined safely.
3. The optimization model provides the optimum distribution of the karst water resources from each source to various water users. It considered the beneficial coefficient for each user. The Fussy analysis is an effective way to determine the beneficial coefficients.
4. Water resource management should consider both the quantity and the quality required by each water user. The results from this study are essential for mine and water managers to coordinate the dewatering effort and distribute the limited resources effectively.

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