Optimum combination of water drainage, water supply and eco-environment protection in coal-accumulated basin of North China

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Abstract The conflict among water drainage, water supply and eco-environment protection is getting more and more serious due to the irrational drainage and exploitation of ground water resources in coal-accumulated basins of North China. Efficient solutions to the conflict are to maintain long-term dynamic balance between input and output of the ground water basins, and to try to improve resourcification of the mine water. All solutions must guarantee the eco-environment quality. This paper presents a new idea of optimum combination of water drainage, water supply and eco-environment protection so as to solve the problem of unstable mine water supply, which is caused by the changeable water drainage for the whole combination system. Both the management of hydraulic techniques and constraints in economy, society, ecology, environment, industrial structural adjustments and sustainable developments have been taken into account. Since the traditional and separate management of different departments of water drainage, water supply and eco-environment protection is broken up, these departments work together to avoid repeated geological survey and specific evaluation calculations so that large amount of national investment can be saved and precise calculation for the whole system can be obtained. In the light of the conflict of water drainage, water supply and eco-environment protection in a typical sector in Jiaozuo coal mine, a case study puts forward an optimum combination scheme, in which a maximum economic benefit objective is constrained by multiple factors. The scheme provides a very important scientific base for finding a sustainable development strategy.

Keywords: combination system of water drainage, water supply and eco-environment protection, optimal combination, resourcification of mine water.

1 Analyses of necessity for the combination

There are three related problems in the basin. It is well known that the major mine-hydrogeological characteristics of the coal accumulated basin in North China display a stereo water-filling structure, which is formed by multi-layer aquifers connected hydraulically together with various kinds of inner or outer boundaries. Mine water hazards have seriously restricted the healthy development of coal industry in China because of more water-filling sources and stronger water-filling capacity in coal mines of the basin. (i) Coal reserves in the basin are threatened by the water hazards. In Fengfeng, Xingtai, Jiaozuo, Zibo, Huaibei and Huainan coal mine districts, for example, it is estimated that coal reserves are threatened by the water hazards up to 52%, 71%, 40%, 60%, 48% and 90% of total prospecting reserves respectively. It is obvious that un-mining phenomenon caused by the water hazards is serious. (ii) Water-bursting accidents under coal layers have seriously influenced safe production. Some statistical data show that there were 17 water-bursting accidents with over 1 m^3/s inflow from 1927 to 1985. (iii) Water drainage is an increasing burden on coal mines threatened by water hazards; high cost of water drainage raises coal prices and reduces profits of the enterprise. On the other hand, it is more and more difficult to meet the demand of water supply in coal mine districts in the basin. The reasons are not only arid and semi-arid weather conditions, but also a large amount of water drainage with deep drawdown in coal mines and irrational water exploitation.

The deterioration of eco-environment is another problem. Phenomena of land surface karst collapse can be found. Many famous karst springs, which are discharge points for the whole karst groundwater system, stop flowing or their discharge rates decrease on a large scale. Desert cremophytes in large areas in west China die because of falling groundwater level[1,2].

These three problems are related and contradictory. In order to solve the problems while ensuring safe mining, meeting water resource demands and slowing down the pace of eco-environment deterioration, it is necessary to study the optimum combination of water drainage, water supply and eco-environment protection in the basin.

2 The state of the art of research and the problems

Although research into the combination of water drainage and water supply started much earlier in some countries, their conception is simple and some shortcomings remain in their study on the theory and pattern of combination[3−5].

China's research history on the combination can be divided into three stages. The first stage is the utilization of mine water. A century ago mine water started to be used as water supply for mines. But the utilization scale and efficiency were quite limited at that time. The second stage is a comprehensive one: mine water was used while water hazards were harnessed. Great progress was made both in theory and practice of the combination. For example, the combination of water drainage and water supply not only means the utilization of mine water, but also means that it is a technique of preventing water hazards. It is unfortunate, however, that the combination research in this stage offered less sense of eco-environment protection[6 − 8]. Optimum combination management of water drainage, water supply and eco-environment protection is the third stage. Main features in this stage are to widen traditional research, and to establish an economic-hydraulic management model, in which safe mining, eco-environment protection and sustainable development demands, etc. are simultaneously considered as constraint conditions[9].

3 Trinity system

The trinity system combines water drainage, water supply and eco-environment quality protection. The water-collecting structures of the system consist of land surface pumping wells in the mines, shallow land surface wells in groundwater recharge areas and artificial relief wells under the mines (see fig. 1). Both integration and coordination for the trinity system are distinguished according to the combination.

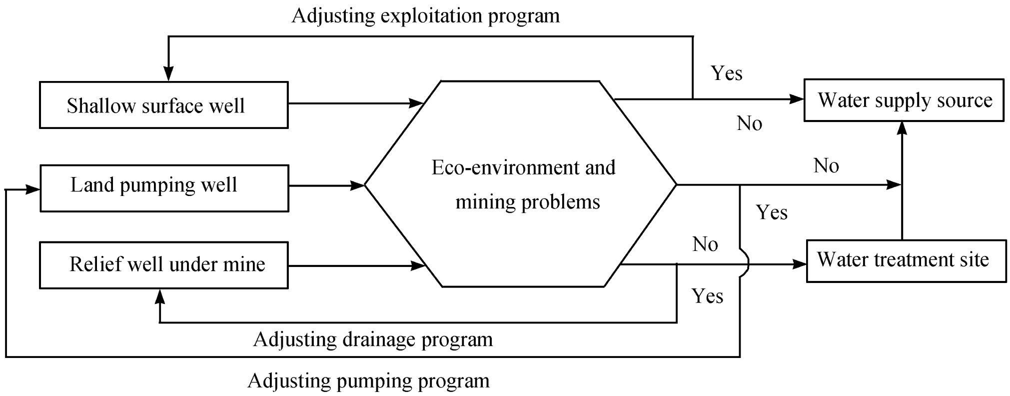

Fig. 1. A sketch map showing arrangement of water collecting structure for the whole combination system.

The integration for the system means to utilize drainage water under the mines and pump water onto the land surface as water supply for different purposes without harming the eco-environmental quality. The coal mines are not only drainage sites, but also water supply sources. The purpose of drilling pumping wells on the land surface is to eliminate special influences on different consumers, which are caused by terminating drainage processes under the mines due to unexpected accidents in mining.

The coordination for the system means to build some water supply sources for different consumers while ensuring eco-environmental quality in groundwater recharge positions, where pumping groundwater is quite effective on lowering groundwater heads in the mine areas. It intercepts in advance the recharging groundwater flow towards the mines, which may not only provide consumers with good quality groundwater, achieve the goal of dropping down groundwater heads in the mines, but also effectively reduce the high costs of drainage and water treatment, which are needed by traditional dewatering measures with large drainage flow rates under the mines. The coordination changes the traditional passive pattern of preventing and controlling groundwater hazards under the mines into that of active surface interception. Both very developed karst flow belts and accumulated groundwater recharge ones under the ground are relatively ideal interceptive coordination positions in the system.

For the integration of the trinity system, artificial relief wells under the mines and the land surface pumping wells mainly penetrate into direct thin bedded karst aquifers interbedded with the mining coal layers, while for the coordination of the system, the shallow land surface wells mainly penetrate into very thick karst aquifer. Therefore, hydrogeological conceptual model for the system involves the multi-layer aquifers connected hydraulically by different inner boundaries. Setting up stereo hydrogeological conceptual models and corresponding mathematical models is a prerequisite for solving the managemental problems for the system.

Management of the trinity system not only considers the effects of lowering groundwater heads and safe operation for water drainage subsystem, but also pays attention to the water demands for water supply subsystem and quality changes for eco-environment protection subsystem. They play the same important role in the whole combination system. It controls the groundwater heads in each aquifer to satisfy the conditions of safe mining with certain water head pressures in the mines, and to guarantee a certain amount of water supply for the mines and near areas, but the maximum drawdown of groundwater must not be exceeded, which may result in lowering eco-environmental quality.

4 Economic-hydraulic management model

In the trinity system management, groundwater resources in the mines and nearby areas, which are assessed on the premise of eco-environment qualities and safe operation in the mines, may be provided as water supply for domestic, industrial and agricultural purposes (see fig. 2). According to water supply prices, drainage (pumping) costs, transportation costs (including pipeline and purchasing the land costs) and groundwater quality treatment costs for the three different water consumers, the optimum management models may automatically allocate to each consumer a certain amount of groundwater resources and a concrete water supply scenario based on comparisons of each consumer's economic contribution to the whole system in objective function. Therefore the management studies on the optimal combination among water drainage, water supply and eco-environment protection involve both the management of groundwater hydraulic techniques and the economic evaluations, eco-environment quality protection and industrial structure programs. In addition to realizing an economic operation, they also guarantee a safe operation which is a key point for the combination of the whole system.

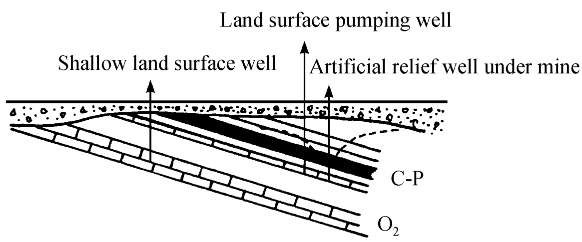

Fig. 2. A sketch map showing the trinity combination.

The management model for the trinity system can reach water supply goals with drainage water under the mines and the land surface pumping water on the premise of ensuring eco-environmental quality. And it can make use of one model to lay down comprehensively optimum management scenarios for each subsystem by means of selecting proper constraints and maximum economic benefit objective produced by multiple water consumers. The model can raise the security and reliability of operation for the whole trinity system, and the drainage water can be forecast for the mines and the management of water supply resource and the evaluation of eco-environment quality can be performed at the same time so as to respectively stop the separate or closed management, of departments of drainage water, water supply and eco-environment protection from geological survey stage to management evaluation. This, in economic aspect, can not only avoid much geological survey and special assessment work which are often repeated by the three departments, and save a lot of funds, but also, in technical aspect, make use of one model to simultaneously consider interference and influence on each other for different groundwater seepage fields so as to guarantee calculating precision of the forecast, the management and the evaluation work. The economic-hydraulic management model can be expressed as follows:

$$
\begin{cases}
\text{Obj: max} \quad Z = \sum_{i=1}^{N_1} \sum_{j=1}^{3} C(i,j)Q_s(i,j)(sp_i - sd_i - st_i - sg_i) \\
\qquad + \sum_{i=1}^{N_2} \sum_{j=1}^{3} C(i,j)Q_g(i,j)(gp_i - gd_i - gt_i - gg_i) \\
\qquad + \sum_{i=1}^{N_3} \sum_{j=1}^{3} C(i,j)Q_n(i,j)(np_i - nd_i - nt_i - ng_i), \\
\text{St} : \leqslant s(k,1) \quad \sum_{i=1}^{N_1} b(k,i,1)Q_s(i,1) + \sum_{i-1}^{N_2} b(k,i,1)Q_g(i,1) + \sum_{i=1}^{N_3} b(k,i,1)Q_n(i,1) \leqslant s'(k,1), \\
s(k,2) \leqslant \sum_{i-1}^{N_1} b(k,i,2)Q_s(i,1) + \sum_{i=1}^{N_2} b(k,i,2)Q_g(i,1) + \sum_{i=1}^{N_3} b(k,i,2)Q_n(i,1) \\
\qquad + \sum_{i=1}^{N_1} b(k,i,1)Q_s(i,2) + \sum_{i=1}^{N_2} b(k,i,1)Q_g(i,2) + \sum_{i=1}^{N_3} b(k,i,1)Q_n(i,2) \leqslant s'(k,2), \\
s(k,2) \leqslant \sum_{i-1}^{N_1} b(k,i,3)Q_3(i,1) + \sum_{i=1}^{N_2} b(k,i,3)Q_g(i,1) + \sum_{i=1}^{N_3} b(k,i,3)Q_n(i,1) \\
\qquad + \sum_{i=1}^{N_1} b(k,i,2)Q_s(i,2) + \sum_{i=1}^{N_2} b(k,i,2)Q_g(i,2) + \sum_{i=1}^{N_3} b(k,i,2)Q_n(i,2) \\
\qquad + \sum_{i=1}^{N_1} b(k,i,3)Q_s(i,3) + \sum_{i=1}^{N_2} b(k,i,1)Q_g(i,3) + \sum_{i=1}^{N_3} b(k,i,1)Q_n(i,3) \leqslant s'(k,3), \\
Q \leqslant \sum_{i=1}^{N_1} \sum_{j=1}^{3} C(i,j)Q_s(i,j) + \sum_{i=1}^{N_2} \sum_{j=1}^{3} C(i,j)Q_g(i,j) + \sum_{i=1}^{N_3} \sum_{j=1}^{3} C(i,j)Q_n(i,j) \leqslant Q', \\
Q_s(i,j) \leqslant q_s(j); Q_g(i,j) \leqslant q_g(i); Q_n(i,j) \leqslant q_n(i); \\
Q_s(i,j) \geqslant 0; Q_g(i,j) \geqslant 0; \; Q_n(i,j) \geqslant 0;
\end{cases}
$$

where $Q_s(i,j), Q_g(i,j), Q_n(i,j)$ are policy making variables of domestic, industrial and agricultural water supply [m^3/d]; sp_i, gp_i, np_i, prices of domestic, industrial and agricultural water supply per cubic meter [RMB yuan]; sd_i, gd_i, nd_i, drainage (pumping) costs of domestic, industrial and agricultural water supply per cubic meter [RMB yuan]; st_i, gt_i, nt_i, transportation costs of domestic, industrial and agricultural water supply per cubic meter [RMB yuan]; sg_i, gg_i, ng_i, quality treatment costs of domestic, industrial and agricultural water supply per cubic meter [RMB yuan]; N_1, N_2, N_3, water collecting structure numbers of domestic, industrial and agricultural water supply; $s(k,i), s'(k,i)$, allowing maximum and minimum drawdowns at point k and time i [m]; Q', extra abstracting water resources in the management system [m^3/a]; Q, water supply demands in the management system [m^3/a].

5 A case study

A typical sector is chosen. It is located in the east of Jiaozuo coal mine, Henan Province, China. It consists of three mines: Hanwang Mine, Yanmazhuang Mine and Jiulishan Mine. The land surface is flat, and the whole area is about 30 km^2. An intermittent river Shanmen flows through the sector from the north to the south. Average annual precipitation in the sector is about 662.3 mm. The precipitation mainly concentrates in June, July, August and September each year.

Strata in the sector consist of very thick limestone in Middle Ordovician, coal-bearing rock series in Permo Carboniferous and loose deposits in Quaternary[10,11].

There are four groups of faulted structures. The first is in northeast-southwest direction such as F_3 and F_1. The second is in the northwest-southeast direction such as Fangzhuang fault. The third is in the east-west direction such as Fenghuangling fault. The last is almost in north-south. These faults are all found to be normal faults with a high degree of dip angle.

Four major aquifers have been found in the sector. The top one is a semi-confined porous aquifer (Q_4). The next one is a very thin bedded limestone aquifer (L_8). The third is a thin bedded limestone aquifer (L_2). The last one at the bottom is a very thick limestone aquifer (O_2).

Objective function of the management model is designed to be maximum economic benefit produced by domestic, industrial and agricultural water supply. Policy making variables of the model are considered as the domestic, industrial and agricultural groundwater supply rates in every management time step, and they are supplied by artificial relief flow wells under the mines, the land surface pumping wells in the mines and the shallow land surface wells in the groundwater recharge areas. All the 135 policy making variables are chosen in the model, 27 for drainage wells under the mines in aquifer L_8, 27 for the land surface pumping wells in the mine districts in aquifer L_8, 27 in aquifer L_2, 27 in aquifer O_2, 27 for the shallow land surface wells in aquifer O_2.

Based on the problems, the following constraint conditions should be considered:

(i) Safe mining constraint with groundwater pressure in aquifer L_8. There are altogether three coal mines in the typical sector, i.e. Hanwang Mine, Yanmazhuang Mine and Jiulishan Mine. Elevations of mining level for these mines are different because it is about –88— -150 m in the second mining level for Hanwang Mine, and -200 m in the second mining level for Yanmazhuang

Mine, and -225 m in the first mining level for Jiulishan Mine. According to mining experiences, pressure-loaded heights for groundwater heads in safe mining state are considered as about 100—130 m. Therefore, the groundwater level drawdowns in the three management time steps for aquifer L_8 at three mines have to be equivalent to safe drawdown values at least in order to prevent groundwater hazards under the mines and to guarantee their safe operation.

(ii) Geological eco-environment quality constraint. In order to prevent groundwater leakage from upper contaminated porous aquifer into bottom one and then to seepage further down to contaminate the thin bedded limestone aquifer in the position of buried outcrop, the groundwater heads in the bottom porous aquifer must keep a certain height, i.e. the groundwater drawdowns in it are not allowed to exceed maximum values.

(iii) Groundwater head constraint at the shallow land surface wells in aquifer O_2. The shallow land surface wells should penetrate in aquifer O_2 in order to avoid geological environment hazards, such as karst collapse and deep karst groundwater contamination. Groundwater head drawdowns in aquifer O_2 for the shallow land surface wells are not allowed to exceed critical values.

(iv) Industrial water supply constraint for the groundwater source in aquifer O_2. The rate of industrial water supply needed by the planned thermal power plant in the north of the sector is designed to be 1.5 m^3/s according to the comprehensive design of the system in the sector. In order to meet the demands of water, the rate of industrial water supply for the groundwater source in aquifer O_2 in every management time step must be equivalent at least to 1.5 m^3/s.

(v) Maximum amount constraint of groundwater resource available for abstraction. In order to maintain the balance of the groundwater system in the sector for a long time and to avoid any harmful results caused by continuous falling of groundwater head, the sum of groundwater abstraction in each management time step is not allowed to exceed the maximum amount of groundwater resource available for abstraction.

Since there is not only water drainage in the mines, but also water supply in the whole combination system, management period for the model is selected from June 1, 1978 to May 31, 1979, in which annual average rate of precipitation is about 50%. Management time steps for the period are divided into three. The first one is from June to September, the second from October to next January, and the last one from next February to May.

According to comprehensive information about actual economic ability, economic development program and industrial structure adjustment in the sector at present and in the near future, and different association forms of water collecting structures among the land surface pumping wells, the shallow land surface wells and artificial relief flow wells under the mines, this paper designs 12 management scenarios, all of which take the safe operation in the trinity system as the most important condition.

After making comparisons of optimum calculation results for the 12 scenarios, this paper comes to a conclusion that scenarios 3-(2)-j (see table 1) is the most ideal and applicable one for the typical sector. This scenario not only considers the effective dewatering advantage of the artificial relief flow wells under the mines and safe stable water supply advantage of the land surface pumping wells, but also pays attention to the disadvantage of low safe guaranty rate for the relief flow wells under the mines for water supply and of large drilling investment in the land surface pumping wells. Meanwhile, the shallow land surface wells in aquifer O_2 in this scenario would not only provide water supply for the thermal power plant as planned, but also play an important role in dewatering the bottom aquifer, which is a major recharge source of groundwater for the mines. If the drainage subsystem under the mines runs normally, this scenario could fully offer the effective dewatering functions of the artificial relief flow wells under the mines, and makes the trinity system operate normally. But if the drainage subsystem has to stop suddenly because of unexpected accidents, the scenario could still fully utilize the land surface pumping wells and the shallow land surface wells, and increase their pumping rates in order to make up for temporary shortage of water supply for the trinity system and to make its economic losses reduced to a minimum extent. Increasing groundwater abstraction rate for the land surface pumping wells and the shallow land surface wells, in fact, is very favorable for harnessing the water-accidents

Table 1 Optimum management result for scenario 3-(2)-j

Node	Water supply depart.	Management time step	Management scenario/$km^3 \cdot d^{-1}$	Objective/ MRMB yuan	Node	Water supply depart.	Management time step	Management scenario/$km^3 \cdot d^{-1}$	Objective/MRMB yuan
7	domestic	1	30.0		175	domestic	1	55.0	
		2	30.0				2	0.0	
		3	30.0				3	0.0	
	industrial	1	15.0			industrial	1	24.904	
		2	15.0				2	0.0	
		3	15.0				3	0.0	
	agricultural	1	3.212 6			agricultural	1	0.0	
		2	0.0				2	0.0	
		3	0.0				3	0.0	
63	domestic	1	55.0		39	domestic	1	0.0	
		2	0.0				2	4.0	
		3	0.0				3	42.0	
	industrial	1	28.328	16.520 6		industrial	1	0.0	
		2	0.0				2	0.0	
		3	0.0				3	0.0	
169	domestic	1	0.0		11	domestic	1	3.645 2	
		2	0.0				2	20.0	
		3	0.0				3	20.0	
	industrial	1	34.303			industrial	1	0.0	
		2	45				2	15.0	
		3	45				3	15.0	
114	domestic	1	0.0		73	domestic	1	0.0	
		2	0.0				2	42.0	
		3	0.0				3	42.0	
	industrial	1	45.0			industrial	1	0.0	
		2	45.0				2	42.0	
		3	45.0				3		
72	domestic	1	5.697 7		178	domestic	1	0.0	
		2	0.0				2	42.0	
		3	0.0				3	42.0	
	industrial	1	45.0			industrial	1	0.0	
		2	45.0				2	0.0	
		3	45.0				3	0.0	
122	domestic	1	0.0						
		2	0.0						
		3	4.0						

under the mines and for recovery production of the mines.

To sum up, this scenario sets up a new pattern for the combination of water drainage, water supply and eco-environment protection. It solves quite well the conflicts between the low safe guaranty rate and the effective dewatering result for the artificial relief flow wells under the mines. It makes full use of beneficial aspect of the conflicts, and meanwhile compensates for the unbeneficial one by arranging the land surface pumping wells in the coal mine districts. Therefore, this scenario should be comprehensive and feasible.

In this scenario, Hanwan Mine (node 7), Yanmazhuang Mine (node 6) and Jiulishan Mine (node 175) are distributed optimally for certain amount of domestic and industrial water supply, but not for much agricultural water supply. The land surface pumping wells (nodes 11, 73, 178) are also distributed for different purposes of water supply. The water supply for the thermal power plant (1.5 m^3/s) is provided by the shallow land surface wells (nodes 169, 114, 72). Comprehensive effects, produced by the above three kinds of water collecting structures, completely satisfy all of the constraint conditions in the management model, and achieve an extremely good economic objective of 16.520 551 million RMB yuan per year. In order to examine the uncertainty of the management model, 12 management scenarios are all tested with sensitive analysis.

6 Conclusion

1) The optimum combination research among water drainage, water supply and eco-environment protection is of great theoretical significance and application value in the basin of North China for solving unbalanced relation between water supply and demands, developing new potential water supply sources and protecting weak eco-environment.

2) The combination research is concerned not only with hydraulic technique management but also with constraints of economic benefits, society, ecology, environment quality, safe mining and sustainable development in the coal mines.

3) The combination model, for the first time, breaks up the closed situation existing for a long time, under which the government departments of drainage water, water supply and eco-environment protection from geological survey stage to management evaluation work respectively. Economically, it can spare the repeated geological survey and special assessment work done by the three departments and save a lot of funds; technically, one model is made use of to cover the interference and influence each other for different groundwater seepage fields so as to guarantee a high calculating precision of the forecast, the management and the evaluation work.

4) The management scenario 3-(2)-j presented in the case study is the most ideal and applicable for the typical sector. This scenario not only makes full use of the effective dewatering advantages of the artificial relief flow wells under the mines and safe stable water supply advantages of the land surface pumping wells, but also pays attention to the disadvantages of low safe guaranty rate for the relief flow wells under the mines for water supply and of large drilling

investment for the land surface pumping wells.

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