Hydraulic-economic optimal management model of mine water resources: an example is Suancigou Coal Mine in western China

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Abstract

A majority of coal mines, located in arid and semi-arid areas of western China, are facing the challenges among mine water resource supply, drainage and ecological environment. Numerical models of groundwater movement in aquifers are built in Suancigou Coal Mine, which are based on hydrogeological conditions analysis and characterization of mine water filling factors. According to the specific requirement of mine water users for water quantity and quality, mine water is treated in tertiary (sewage) treatment. The optimized hydraulic-economic management model is analyzed by control, treatment, utilization, recharge and ecological environmental protection of mine water. The model solves the mine water resource problems in Suancigou Coal Mine, and supports it to realize the sustainable development and utilization of groundwater resources, which would contribute to tremendous economic benefits.

Keywords: mine water, numerical model, treatment and utilization of mine water resource, hydraulic-economic optimal management model

Introduction

Mine water, not only threatens coal mine production safety, but potentially leads to environmental pollution and a great waste of water resources due to unscientific discharge (Qian and Miao et al. 2007). At present, China' s coal production is about 3.7 billion tons per year, while mine water drainage is up to 7.2 billion tons annually (Wu 2014), which strongly proves that mine water resource is one of largest associated resources during coal mining (Wu and Li 2009). In recent years, with awareness-raising of protecting water resources and environment, and driving by maximization of enterprises' s interests, the utilization rate of mine water has increased gradually (He and Yang et al. 2008). However, value of utilization rate is still low in China, which is of huge differences between different regions, and far from the goal set by the government. Optimizing the combination model of mine water control, treatment, utilization, recharge and ecological environment protection in Suancigou Coal Mine is to treat and utilize mine water in order to maximize of economic benefits on the premise of ensuring mine safety production. Based on the analysis of mine hydrogeological variations and mine water filling factors, the numerical model of mine groundwater is established and the characteristics of the groundwater flow field under the current mining conditions are simulated. Mine water treatment technology coordinated by ground and underground is put forward according to water quality and quantity requirement of users. Finally, the hydraulic-economic optimal management model of mine water control, treatment, utilization, recharge and Eco-environment protection is established.

General situation of mine

Suancigou Coal Mine, located in Junggar of Inner Mongolia, China (Fig. 1), is developed by inclined shaft with a face of about 49.8

Figure 1 Schematic map of traffic location in Suancigou Coal Mine

km². At present, the main mining areas are the 4th coal seam of the Lower Permian Shanxi Formation and the 6th coal seam of the Upper Carboniferous Taiyuan Formation. The landscape of the mining area belongs to the erosive hilly landform of the plateau, and the branched valleys are well developed in the Ordos Loess Plateau. The topography is generally high in the north and low in the south. Further more, it shows a trend of high in the middle and low in the East and west. The climate of Ordos is dry semi-desert plateau continental arid climate. Large temperature difference between day and night, and the annual average temperature is between 5.3 and 7.6 °C. Rainfall mostly concentrated from July to September, which making for 60% to 70% of the total precipitation.

Groundwater aquifers in Suancigou Coal Mine mainly include porous aquifers of Quaternary loose rocks, fractured aquifers of Carboniferous-Permian clastic rocks and karst aquifers of Ordovician carbonate rocks. The hydrogeochemistry analysis results and environment isotope test values show that the hydraulic relationship between different aquifers is weak.

Mine water control

By analyzing the mine water filling factors and the current mine production, the main mine water source in Suancigou is the sandstone fissure water in coal roof and the goaf water respectively. It enters the underground mine mainly in three ways: (1) borehole drilling, exploring and drainage water holes in mine; (2) water drainage boreholes in goaf; (3) faults and water-conducting fissure zone. Based on both "upper three zones" model (Ma and Wu 2008) and empirical formula that take the water-conducting fracture zone height into account, risk assessment of roof water-inrush is obtained by characterization of roof rock assemblage and water-rich analysis of roof aquifer formation. Firstly, risk assessment results show that the fissure water in the aquifer formations of the Carboniferous Taiyuan Formation, Permian Shanxi Formation and Lower Shihezi Formation can flow into the mine through the water-conducting fissure zone. Secondly, not only water yield property of water-bearing rock groups affected by water-conducting fissure zones are very weak, but water yield property of water-bearing rock groups not affected by water-conducting fissure zones are with similar features. In addition, water yield property is relatively strong about the pore aquifers of loose rocks in Quaternary valleys which are not affected by water-conducting fissure zones. Moreover, the aquicludes underlying Quaternary pore aquifers have better integrity and continuity, and their thickness is fairly large. Hence, water inrush from the roof will not occur in general.

According to mine geology and hydrogeology condition, the numerical model of groundwater movement in Suancigou Coal Mine is established by MODFLOW module in Groundwater Modelling System (GMS) in order to better shown the groundwater movement. The hydrogeological parameters of the model are calibrated and evaluated according to the dynamic data of karst water level with observation boreholes. Then the groundwater flow field under current mining conditions are simulated. The results show that the fissure water in both Shanxi Formation aquifer of Permian Lower Shihezi Formation and Carboniferous Taiyuan Formation aquifer of Permian Shanxi Formation finally forms a cone when groundwater seeps into the mining area through the water-conducting fissure zone.

Mine Water Treatment, Utilization and Recharge

Whenever groundwater flows into the water filling aquifer in mines, it will be reacting with surrounding rocks and coal seams by a series of chemical reactions. Meanwhile, mining activities will pollute water quality as well. Therefore, the characteristics of mine water quality are almost same with the hydrochemical characteristics of water-filled water source, and probably be infected by other factors as well.

The combined process of pretreatment, primary treatment and secondary treatment is adopted in mine water treatment system. Pretreatment, including diversion of clear water and waste water, and goaf purification, is a type of underground treatment. Primary treatment is processed above ground, which includes clarification and disinfection. Secondary treatment, effectively remove dissolved salt, colloid, bacteria, viruses, bacterial endotoxins and most organic substances in mine water, is a reversing osmosis membrane treatment technology.

Users of mine water in Suancigou mine, power plants, underground dust removal and drilling (underground production I), bathhouses, underground equipment cooling (underground production II), ground recharge, coal washery and mining area greening, are determined based on water requirement of Suancigou Mine and its surrounding enterprises, and the principle of water supply by mine water quality.

Mine water that under ground can be used in coal washing plant after processed by the ground horizontal flow sedimentation tank; primary treatment water mainly roles as greening or dust removal; secondary treatment water mainly acted as water source of bathing, power plants, and underground equipment cooling. Ground recharge plays the role as artificial storage, where redundant mine water source, processed by secondary treatment that meets the requirement of water quality for water recharging, can be recharged to groundwater aquifers.

To protect and adjust the utilization of mine water resources, O_{m-1} karst water pumping borehole is selected as injection well which is 560 m deep and exposed high permeability karst aquifer formation about 200 m. In groundwater injection test, the injection rate ups to 1440 m^3/h with natural pressure condition (water pressure is about 3 MPa in natural state). Thus, the recharge borehole works well, and is well suitable for adjusting mine water resources under current mine water inflow condition.

Ecological environment protection

Discharge rate of mine water in Suancigou Coal drops to zero after the above treatment, and neither threaten or damage the hydro-environment of surface rivers, soil and groundwater surrounding the mine. As karst water acts as the mainly water source for industrial and residential water supply in this region, mine water resources utilization cannot only reduce the consumption of the water source, but also supplement the water source by surface water injection. Therefore, it would be benefit to the local ecological and hydrological environment protection, and conducive to the sustainable use and development of karst water resources at the same time (Gunson and Klein et al. 2012).

Hydraulic-Economic Optimal Management Model

In view of the mine programming of Suancigou Mine, management periods are divided into two 2.5-years. Under the premise of ensuring the safety of mine production (that is, no mine water hazard occurs), the hydraulic-economic optimal management model, based on both demands of users for mine water resources and water quality, and various quality cost of mine water treatment, is established in Suancigou Coal Mine aiming at maximizing economic benefits by groundwater dynamics theory and operation research, including mine water resources control, treatment, utilization, recharge and environmental protection (Wu and Wang et al. 2010).

The optimal management model is composed of objective function and constraint conditions. First of all, the water supply price of users is formulated specially according to regulations of regional industrial water price. Then, customized water quality requirements of various users to determine their water quality treatment cost separately. After that, mine water transmission cost from sewage plant to various users is calculated accordingly. Finally, followed objective functions are set up with the maximum economic benefit of the coal mine.

Where N_1, N_2, N_3, N_4, N_5, N_6, N_7 are the number of water supply wells for the power plant, underground production I, bathhouse, underground production II, surface recharge, coal washery, and greening of the mining area, respectively.

$Q_a(i,j), Q_b(i,j), Q_c(i,j), Q_d(i,j), Q_e(i,j), Q_f(i,j), Q_g(i,j)$ indicates the single well water supply rate for power plant, underground production I, bathhouse, underground production II, surface recharge, coal washery and greening of mining area in the first and second periods. gf_1 denotes water supply price of power plant; gf_2 denotes water supply price of underground production I, bathhouse, coal washery, underground production II and greening of mining area respectively; gf_3 represents water supply price of ground recharge; tf, cf_1, cf_2 respectively represents the cost of extraction and first treatment and second treatment of mine water; sf_1 represents water transmission cost of power plant; sf_2 represents water transmission cost of underground production I, ground recharge and underground production II; sf_3 is water conveyance cost of bathhouse; sf_4 is water conveyance cost of coal washery; sf_5 is water conveyance cost of greening, and $C(i,j)$ is the days of planning period.

$$MaxZ = \sum_{i=1}^{N_1}\sum_{j=1}^{2} C(i,j)(gf_1 - tf - cf_1 - cf_2 - sf_1)Q_a(i,j) + \sum_{i=1}^{N_2}\sum_{j=1}^{2} C(i,j)(gf_2 - tf - cf_1 - cf_2 - sf_2)Q_b(i,j) + \sum_{i=1}^{N_3}\sum_{j=1}^{2} C(i,j)(gf_2 - tf - cf_1 - cf_2 - sf_3)Q_c(i,j) + \sum_{i=1}^{N_4}\sum_{j=1}^{2} C(i,j)(gf_3 - tf - cf_1 - sf_2)Q_d(i,j) + \sum_{i=1}^{N_5}\sum_{j=1}^{2} C(i,j)(gf_2 - tf - sf_4)Q_e(i,j) + \sum_{i=1}^{N_6}\sum_{j=1}^{2} C(i,j)(gf_2 - tf - cf_1 - cf_2 - sf_2)Q_f(i,j) + \sum_{i=1}^{N_7}\sum_{j=1}^{2} C(i,j)(gf_2 - tf - cf_1 - sf_5)Q_g(i,j) \quad (1)$$

The constraint conditions include both the drawdown value or range of groundwater level in aquifers disturbed by coal seam mining, and the specific water demand values of each user. Regarding to the area where the mine has been exploited, the groundwater drawdown of the controlled observation points satisfies the following constraint conditions:

$$\sum_{i=1}^{N_1}\beta(k,i,1)\,Q_a(i,1)+\sum_{i=1}^{N_2}\beta(k,i,1)\,Q_b(i,1)+\sum_{i=1}^{N_3}\beta(k,i,1)\,Q_c(i,1)+\sum_{i=1}^{N_4}\beta(k,i,1)\,Q_d(i,1)+\sum_{i=1}^{N_5}\beta(k,i,1)\,Q_e(i,1)+\sum_{i=1}^{N_6}\beta(k,i,1)\,Q_f(i,1)+\sum_{i=1}^{N_7}\beta(k,i,1)\,Q_g(i,1)=s(k,1) \quad (2)$$

$$\sum_{i=1}^{N_1}\beta(k,i,2)\,Q_a(i,1)+\sum_{i=1}^{N_1}\beta(k,i,1)\,Q_a(i,2)+\sum_{i=1}^{N_2}\beta(k,i,2)\,Q_b(i,1)+\sum_{i=1}^{N_2}\beta(k,i,1)\,Q_b(i,2)+\sum_{i=1}^{N_3}\beta(k,i,2)\,Q_c(i,1)+\sum_{i=1}^{N_3}\beta(k,i,1)\,Q_c(i,2)+\sum_{i=1}^{N_4}\beta(k,i,2)\,Q_d(i,1)+\sum_{i=1}^{N_4}\beta(k,i,1)\,Q_d(i,2)+\sum_{i=1}^{N_5}\beta(k,i,2)\,Q_e(i,1)+\sum_{i=1}^{N_5}\beta(k,i,1)\,Q_e(i,2)+\sum_{i=1}^{N_6}\beta(k,i,2)\,Q_f(i,1)+\sum_{i=1}^{N_6}\beta(k,i,1)\,Q_f(i,2)+\sum_{i=1}^{N_7}\beta(k,i,2)\,Q_g(i,1)+\sum_{i=1}^{N_7}\beta(k,i,1)\,Q_g(i,2)=s(k,2) \quad (3)$$

To the planned mining area, groundwater drawdown of the controlled observation points satisfies the following constraint conditions:

$$\sum_{i=1}^{N_1}\beta(k,i,1)\,Q_a(i,1)+\sum_{i=1}^{N_2}\beta(k,i,1)\,Q_b(i,1)+\sum_{i=1}^{N_3}\beta(k,i,1)\,Q_c(i,1)+\sum_{i=1}^{N_4}\beta(k,i,1)\,Q_d(i,1)+\sum_{i=1}^{N_5}\beta(k,i,1)\,Q_e(i,1)+\sum_{i=1}^{N_6}\beta(k,i,1)\,Q_f(i,1)+\sum_{i=1}^{N_7}\beta(k,i,1)\,Q_g(i,1)\le s(k,1) \quad (4)$$

$$\sum_{i=1}^{N_1}\beta(k,i,2)\,Q_a(i,1)+\sum_{i=1}^{N_1}\beta(k,i,1)\,Q_a(i,2)+\sum_{i=1}^{N_2}\beta(k,i,2)\,Q_b(i,1)+\sum_{i=1}^{N_2}\beta(k,i,1)\,Q_b(i,2)+\sum_{i=1}^{N_3}\beta(k,i,2)\,Q_c(i,1)+\sum_{i=1}^{N_3}\beta(k,i,1)\,Q_c(i,2)+\sum_{i=1}^{N_4}\beta(k,i,2)\,Q_d(i,1)+\sum_{i=1}^{N_4}\beta(k,i,1)\,Q_d(i,2)+\sum_{i=1}^{N_5}\beta(k,i,2)\,Q_e(i,1)+\sum_{i=1}^{N_5}\beta(k,i,1)\,Q_e(i,2)+\sum_{i=1}^{N_6}\beta(k,i,2)\,Q_f(i,1)+\sum_{i=1}^{N_6}\beta(k,i,1)\,Q_f(i,2)+\sum_{i=1}^{N_7}\beta(k,i,2)\,Q_g(i,1)+\sum_{i=1}^{N_7}\beta(k,i,1)\,Q_g(i,2)=s(k,2) \quad (5)$$

The customized amount of mine water required by each user meets the following constraint conditions:

$$Q_1\le\sum_{i=1}^{N_1}Q_a(i,1)\le Q_2,\ Q_1\le\sum_{i=1}^{N_1}Q_a(i,2)\le Q_2,\ Q_3\le\sum_{i=1}^{N_2}Q_b(i,1)\le Q_4,\ Q_3\le\sum_{i=1}^{N_2}Q_b(i,2)\le Q_4,\ Q_5\le\sum_{i=1}^{N_3}Q_c(i,1)\le Q_6,\ Q_5\le\sum_{i=1}^{N_3}Q_c(i,2)\le Q_6,\ Q_7\le\sum_{i=1}^{N_4}Q_d(i,1)\le Q_8,\ Q_7\le\sum_{i=1}^{N_4}Q_d(i,2)\le Q_8,\ Q_9\le\sum_{i=1}^{N_5}Q_e(i,1)\le Q_{10},\ Q_9\le\sum_{i=1}^{N_5}Q_e(i,2)\le Q_{10},\ Q_{11}\le\sum_{i=1}^{N_6}Q_f(i,1)\le Q_{12},\ Q_{11}\le\sum_{i=1}^{N_6}Q_f(i,2)\le Q_{12},\ Q_{13}\le\sum_{i=1}^{N_7}Q_g(i,1)\le Q_{14},\ Q_{13}\le\sum_{i=1}^{N_7}Q_g(i,2)\le Q_{14} \quad (6)$$

β(k,i,1) represents the unit impulse response function in the first period, and *β(k,i,2)* represents that in the second period. $Q_a(i,1)$, $Q_b(i,1)$, $Q_c(i,1)$, $Q_d(i,1)$, $Q_e(i,1)$, $Q_f(i,1)$, $Q_g(i,1)$ are the single well water supply for power plant, underground production I, bathhouse, underground production II, surface recharge, coal washery and mining area greening in the first period, separately. $Q_a(i,2)$, $Q_b(i,2)$, $Q_c(i,2)$, $Q_d(i,2)$, $Q_e(i,2)$, $Q_f(i,2)$, $Q_g(i,2)$ denote that in the second period. $s(k,1)$ is the water level drawdown value of the control observation point in the first period, and $s(k,2)$ is the water level drawdown value of the control observation point in the second period. Q_1, Q_2 show the upper and lower limits of water demand for the power plant. Q_3 and Q_4 form the upper and lower limits of water demand for underground production I. Q_5, Q_6 respectively indicate the upper and lower limits of water demand for the bathhouses. Q_7, Q_8 represent the upper and lower limits of water demand for underground production II. Q_9, Q_{10} indicate the upper and lower limits of water demand for surface recharge. Q_{11}, Q_{12} are the upper and lower limits of water demand for coal washing plant. Q_{13}, Q_{14} indicate both the upper and lower limits of mining area greening.

Conclusions

The relationship between the optimal combination of mine water control, treatment, utilization, recharge and ecological environment protection is systematically researched by taking prevention and control of mine water disaster, mine water decontamination, and water resources utilization as the goal in Suancigou Coal Mine. A groundwater movement numerical model is established based on hydrogeological conditions analysis and mine water filling factors characterization. By tertiary (sewage) treatment of mine water resources, specific water supply for different users is realized, and the injection test shows that recharge well can realize the function of mine water resources adjustment in coal mine. The optimal hydraulic-economic management model of mine water control, treatment, utilization, recharge and eco-environmental protection in Suancigou Coal Mine is established, which scientifically improves the management level in coal mines, in order to realize zero discharge rate of mine water, protection of ecological and hydrological environment, and achieves maximum economic.

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References

Minggao Qian, Xiexing Miao, Jialin Xu (2007) Green mining of coal resources harmonizing with environment. Journal of China Coal Society 32(1):1-7

Qiang Wu (2014) Progress, problems and prospects of prevention and control technology of mine water and reutilization in China. Journal of China Coal Society 39(5): 795-805, doi:10.13225/j.cnki.jccs.2014.0478

Qiang Wu, Duo Li (2009) Research of "coal-water" double-resources mine construction and development. Coal Geology of China 21(3):32-35

Xuwen He, Jing Yang, Linan Shao, Fuqin Li, Xin Wang (2008) Problem and countermeasure of mine water resource regeneration in china. Journal of China Coal Society 33(1):63-66, doi:10.13225/j.cnki.jccs.2008.01.001

Yajie Ma, Qiang Wu, Zhiyan Zhang, Yiqing Hong, Liwen Guo, Hongsheng Tian, Lige Zhang (2008) Research on prediction of water conducted fissure height in roof of coal mining seam. Coal Science and Technology 36(5):59-62

A.J. Gunson, B Klein, M Veiga, S Dunbar (2012) Reducing mine water requirements. Journal of Cleaner Production 21(1):71-82, doi:10.1016/j.jclepro.2011.08.020

Qiang Wu, Zhiqiang Wang, Zhouke Guo, Dangyu Zhang, Yajie Chen, Pengfei Zhao, et al. (2010) A research on an optimized five-in-one combination of mine water control, treatment, utilization, back-filling and environment friendly treatment. China Coal 36(2):109-112