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Research article

Equilibrium strategy-based optimization method for the coal-water conflict: A perspective from China

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ABSTRACT

Environmental water problems have become increasingly severe, with the coal-water conflict becoming one of the most difficult issues in large scale coal mining regions. In this paper, a bi-level optimization model based on the Stackelberg–Nash equilibrium strategy with fuzzy coefficients is developed to deal with environmental water problems in large scale coal fields, in which both the groundwater quality and quantity are considered. Using the proposed model, and fully considering the relationship between the authority and the collieries and also the equilibrium between economic development and environmental protection, an environmental protection based mining quotas competition mechanism is established. To deal with the inherent uncertainties, the model is defuzzified using a possibility measure, and a solution approach based on the Karush-Kuhn-Tucker condition is designed to search for the solutions. A case study is presented to demonstrate the practicality and efficiency of the model, and different constraint violation risk levels and related results are also obtained. The results showed that under the environmental protection based mining quotas competition mechanism, collieries attempt to conduct environmentally friendly exploitation to seek greater mining quotas. This demonstrates the practicality and efficiency in the proposed model of reducing the coal-water conflict. Finally, a comprehensive discussion is provided and some propositions is given as a foundation for the proposed management recommendations.

1. Introduction

Coal is the second most important fuel currently used by mankind, accounting for over 25% of the worlds primary energy supply (Höök, 2013; Heinberg and Fridley, 2010). Water is also a resource that nobody can live without (Gleick, 2003; Vöröosmarty et al., 2000). However, for safety, significant quantities of groundwater are discharged in underground mining (Younger and Wolkersdorfer, 2004; Sun et al. 2012), which has many pollutants and bring further damage to local water environment (Wolkersdorfer and Bowell, 2005; Silva et al. 2013). Encouraged by high economic revenue, many coal production areas have been extensively exploited, which has already resulted in many serious water environmental problems, such as groundwater table depression and regional water quality deterioration (Younger, 2001). This situation can be generally summarized as the coal-water conflict. In recent years, with the rapid development of the world economy, the consumption of coal has been increasing which results that the coal-water conflict has becoming increasingly worse (Yuan et al. 2008; Feng et al. 2009).

Fortunately, many people have already noticed this issue and have already done some study on it. Many policies and laws have been formulated to reduce the harmful effects of this conflict around the world, such as the Mineral Resources Law of the People's Republic of China, the National Environmental Policy Act of the United States and Japan's Mining Law. Younger and Wolkersdorfer (2004) studied the impact of mining on the fresh water environment deeply and proposed a decision framework for long-term mine water management at the catchment scale based on an Environmental Information System. Aryafar et al. (2013) proposed a fuzzy analytical hierarchy process based on an environmental impact assessment method to control the environmental situation in a mining district. Qiao et al. (2011) studied the influence of coal mining on regional karst groundwater system, established a three-dimensional groundwater flow model and then applied it to several scenarios to explore the quantitative influence

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of mining activities on the water environment. There have also been many studies which have examined methods to improve coal mining technologies to resolve the coal-water conflict (Bian et al. 2009; Gazea et al. 1996). However, the actual situation is still not satisfactory and some other methods are still needed. As far as is known, to date there has been no research which has used an equilibrium strategy-based optimization method to solve this conflict. Equilibrium strategy has been used to solve conflicts in many other fields and have already achieved some significant results. Xu et al. (2012) proposed an bi-level optimization model based on equilibrium strategy with fuzzy random variables to solve the conflict in a regional water resources allocation problems, Küçükaydin, et al. (2011) proposed an equilibrium theory based bi-level programming model to cope with competitive facility location problem and Gzara (2013) used equilibrium theory to deal with the conflict between risks and costs in hazardous material transportation and came to some solid conclusions. These excellent works have encouraged us to use equilibrium strategy to solve the coal-water conflict.

China is the second most populous country in the world and the fourth largest in area with 1.3 billion people and 9.6 million square kilometers of national territory. During the past decades, China has experienced remarkable development, which has been supported by a huge rise in energy consumption, especially coal (Li and Leung, 2012; Feng et al. 2009). China consumes more than half the world's total consumption of coal, with over 83×10^9*tons* coal of usable reserves having been extracted, and 98×10^9*tons* planning to be extracted in the future (Sun et al. 2012; Cattaneo et al. 2011). However, only a quarter of the worlds per capita water availability is available in China and is now still exacerbating (Liu and Diamond, 2005). Further, water resources are spread unevenly across the country, with northern China, the main coal producing region, having only one third of the per capita quantity of southern China, which further aggravates the coal-water conflict (Liu and Diamond, 2005; Pan et al. 2012). So in this paper, we chose China as an example on which to use the equilibrium strategy-based optimization method to solve this conflict.

Based on the above discussion, this paper proposes an optimization method based on the Stackelberg–Nash (SN) equilibrium under an uncertain environment to solve the coal-water conflict. In Section 2, detail of coal-water conflict mechanism and the actual situation in China and how equilibrium strategy can solve this conflict are explained in preparation for the establishment of the mathematical model. In Section 3, a mathematical model based on SN equilibrium theory is built as an abstract of the real problem and then a solution method to the model is given. A case study is then presented in Section 4 to demonstrate the significance of the proposed models and solution method. In Section 5, we analyze the results of the model and provide a comprehensive discussion. A comparative study and some management recommendations are also given in this section. Conclusions are given in Section 6.

2. Key problem statement

To develop an equilibrium strategy-based optimization method to solve the coal-water conflict in China, some basic background and descriptions are introduced.

In Chinese large scale coal fields, there are two kinds of related decision makers whose decisions affect the coal mining industry: the regional authority and the collieries. The regional authority, who acts on behalf of the public, considers the public interests that are of benefit to the whole region, so both economic development and environmental protection need to be taken into account to achieve environmentally-friendly development goals. Therefore, the regional authority's objective is to maximize total financial revenue under an environmental carrying capacity constraint. The government has the authority to allocate mining quotas to each sub-colliery while at the same time considering economic development and environmental protection equilibrium. On the other side, the collieries need to develop a mining plan according to the government quota. All collieries are independent of each other, and they individually pursue the largest possible profits. Indeed, as geological conditions are not the same, coal quality from different coal-seams is also different (Ward, 2002), so the market price and the unit revenue vary. The per tonne coal drainage coefficient at different coal seams is different and the concentration of pollutants in the drainage also varies (Falcon, 1989). Based on these facts, collieries are able to determine a reasonable production scheme across each coal seam to achieve environmentally friendly exploitation under the government quota to maximize benefits and control the environmental impact on the water within the government mandated provisions.

In such situations, the local government first decides on the exploitation quota for each colliery using historical data. Then, the collieries in the region develop their own plans according to the government decision. At the same time, the local authority is also able to adjust its initial decision depending on the decisions of the followers. This type of decision making is similar to a Stackelberg game. To determine the most reasonable development, this game needs to be abstracted as a mathematical problem which can then be calculated. Bi-level programming can just be used to describe such a game, in which the local government has the higher authority, and the sub-collieries in the area are the subordinates, even though they are relatively independent decision makers. Therefore in such a game, the upper level programming represents the main decision body which makes decisions about the total amount that each collieries in its administration district is allowed to exploit. The lower level represents the main collieries in the area, each of which must decide on the total mining amount allocation for their respective coal streams. Because this leader-follower behavior between the two decision maker levels is a Stackelberg game, an SN equilibrium between the local government and the coal mines can be found. The structure of this bi-level programming is shown in Fig. 1.

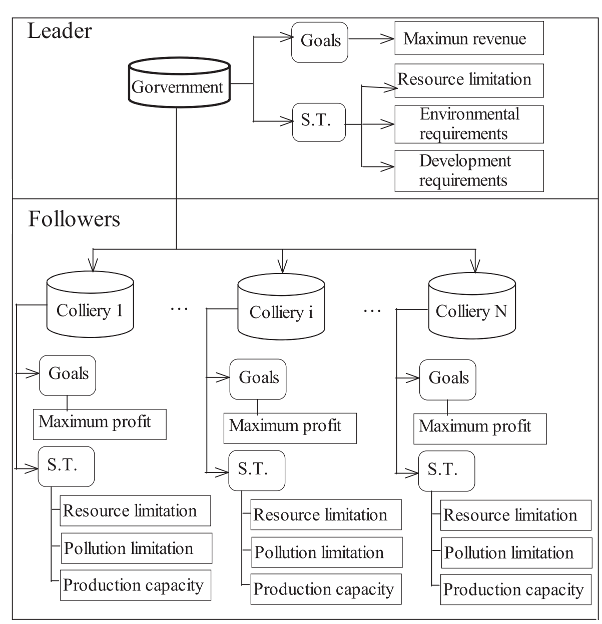

Fig. 1. Flowchart of mining quota allocation.