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Determining the scale of coal mining in an ecologically fragile mining area under the constraint of water resources carrying capacity

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ABSTRACT

A reasonable mining scale is very important for the development of mining areas. In view of the lack of water resources in arid and semi-arid areas, this paper studies the scale of coal mining in arid and semi-arid areas under the constraint of the water resources carrying capacity (WRCC) with the aim of realizing the conservation mining of ecological environment. From the perspectives of market demand side, production side and the constraint side, a "trinity" decision model was constructed to investigate the main factors influencing the scale of coal mining. By introducing the optimal control theory with profit taken as objective function, the coal price and coal reserves were regarded as boundary conditions, and WRCC was set as constraint condition. Based on *H-J-B* equation algorithm, the decision-making equation for mining scale under the constraints of market demand and WRCC was obtained. Through comparing the mining scales under the two constraints, the mode of "water-based mining scale" was formulated, which is conductive for realizing the balance between coal mining and ecological environment development.

1. Introduction

China is a major producer and consumer of coal. The ecological problems in coal mining areas have become a hot topic of concern in all fields of the society (Qian, 2018). As the concept of "green development" has become a social consensus and national strategy, the ecological environment of coal mining area and scientific mining have become the focuses in academic circles. With the implementation of "The Belt and Road Initiative", Xinjiang has become the base of China's coal strategy. Located in arid and semi-arid areas, Xinjiang has less rainfall and fragile ecology. Human activities such as coal mining may cause land desertification (Papendiek et al., 2016). If the ecological environment is destroyed, the environment restoration costs will be enormous. Xinjiang's coal reserves account for more than one third of the whole country, but water resources in Xinjiang are extremely scarce. Due to the "imbalanced distribution of coal and water" in Xinjiang, the lack of water resources is not only a bottleneck inhibiting the development of coal industry, but also a factor restricting the scale of coal mining (Xie, 2012). How to resolve the contradiction between coal mining and water resources protection has become a thorny problem in this area. Scientific mining is the key to solve this problem (Hobbs, 2008; Kirsch, 2010; Ashkan, 2018). The premise of scientific mining is obtaining reasonable scale of coal mining and scientific planning of pre-mining (Green et al., 2019).

As mentioned before, the contradiction between ecological environment development and coal mining has become an urgent problem to be solved. The key to solve this problem is to maintain the enough amount of water resources to support the ecological environment in mining area after coal mining. To determine the threshold of WRCC in the mining area during the coal mining process, a preliminary exploration was carried out (Chi et al., 2019). The WRCC and its dynamic change in the ecological fragile mining area during coal mining were evaluated (Wang and Xu, 2015). To figure out whether the scale of coal mining can meet the market demand under the constraint of WRCC, the analysis of coal mining scale is needed (Neal and Turner, 2000; Ren et al., 2015). With regard to the research on mining scale, many scholars have expounded the basic ideas and concepts from different angles. Their basic ideas are based on sustainable development and ecological environment protection, i.e. achieving safe and efficient output of coal without causing serious damage to the ecological environment of the

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mining area. Many scholars also carried out tentative predictions of the scale of scientific mining by introducing prediction models and calculation methods into the decision-making models.

At present, there are mainly two types of methods to predict the scale of resource mining. The first one is to establish a system model to analyze the main influencing factors, such as P–S-R model (Pressure-State-Response) as well as its evolutionary models (Hotelling, 1991; Stiglitz, 1974; Solow, 1976; Rapport, 1979) (D-S-R model (Driving Force-State-Response), P–S-R-P model (Pressure-State-Response-Potential), D-P-S-R-C model (Driving Force-Pressure-State-Response-Control) and D-P-S-I-R model (Driving Force-Pressure-State-Impact-Response)). The P–S-R model was presented by Canadian scholars David and Tony in 1979 (Solow, 1976; Mohr et al., 2011; Khosrow, 2018). Then, the applicability and effectiveness of the S-R model were revised by the International Organization for Economic Cooperation and Development (OECD). On this basis, the concept of P–S-R model was summarized and applied to the world environmental situation. These conceptual models emphasize the evaluation indexes such as “pressure”, “state” and “response”, but seldom focus on the dynamic interaction of influencing factors. Therefore, they are only suitable for studying the apparent static phenomena in the system. Researches on such type of model mainly focus on the prediction of mining scale of mineral resources, in order to achieve the estimation of future mining amount. For the second type of method, mathematical theory is introduced into decision-making process. For example, Hubbert et al. used logistic model to simulate and predict the global coal mining scale (Hotelling, 1991). They believed that the coal mining scale should conform to the “bell-shaped” curve, that is, increasing at the initial stage, then maintaining a stable growth, reaching peaks, and finally declining gradually. Later, Mohr et al. (2011) and Tao et al. (2007) speculated on the scale of energy exploitation in Australia and China according to Hubbert’s theory, expounded the main factors affecting the scale of coal mining, and concluded that China’s mining peak scale would reach 3339 to 4452 million tons between 2025 and 2032. The second type of method is to take main influencing factors as restriction conditions and use mathematical statistics theory to obtain the predicted value of mining scale. However, such type of method does not take into account the impact of incalculable factors such as policy and environment, so long-term prediction results will deviate from the actual results.

To obtain a reasonable scale of coal mining, many influencing factors need to be considered. Previous studies mainly focused on the influence of economy and technology, but ignored the objective factors such as water resources and ecological environment, resulting in the unlimited expansion of coal mining. The scale of coal mining showed a trend of “surplus-adjustment-stable-surplus”. (Donnelly et al., 2008; Adiansyah et al., 2017; Haak et al., 2017). Generally speaking, the analysis of mining scale is based on the production side and the demand side. However, there are very few researches considering the two sides as well as additional restrictive factors at the same time. Some scholars think that coal resource reserves and mining technology are the basic factors affecting mining scale, and coal resource reserve is the basis for determining the mining scale. Mining technology, mining cost, safety and efficiency have great impacts on mining scale. These factors can be summed up as the production side. Evaluating the mining scale from only the production side without considering the influence of market demand and other factors may cause overcapacity or oversupply. Therefore, the influences of market demand, benefit and other factors should also be considered in the determination of mining scale, that is, the demand capacity of demand side must be considered in the determination of rational mining scale, so that the balance between supply and demand can be realize to ensure the scientific mining and sustainable development of coal industry. As people pay more and more attention to the ecological environment, some scholars realize that the environment is also an important factor restricting the mining scale. In particular, current researches on water resources in mining areas have been deepened and the ecological environment has been increasingly regarded as a significant impact of mining scale. The mining scale beyond the limits of ecological environment or water resources carrying capacity will lead to the worsening of WRCC or even the entire ecological environment in the coal mining area. Therefore, the production side and the demand side should be simultaneously considered in the determination of coal mining scale. Only by effectively combining the two sides and considering the influence of external additional factors can we obtain a more reasonable scale of coal mining. In fact, regarding the influence to coal mining scale, production side and demand side are indispensable and restrict each other. Considering the limited water resources in Yili mining area, a prediction model was put forward in this study considering the production side, the market demand side and the WRCC of coal enterprises as constraints. The reasonable scale of coal mining in the ecologically fragile mining area was investigated. This study is of practical significance for the sustainable development of ecologically fragile mining areas as well as of academic value for the researches on the decision-making theory.

2. Influencing factors of mining scale

Due to the non-reproducibility of coal, many scholars have made great efforts in determining a reasonable scale of coal mining. How to determine a reasonable mining scale is a problem that has been studied by the academia. The first task is to find the main factors affecting mining scale. According to the previous research and combining the actual situation of ecologically fragile mining areas, this paper selects coal reserves, market demand, mining conditions, ecological environment, safety and efficiency, mining costs (mining methods), benefits and WRCC as the main factors affecting the scale of coal mining in ecologically fragile mining areas (Booth, 2006; Zhang et al., 2010; Xie, 2012; Li, 2017; Qian, 2018).

1) Coal reserves directly determine the recoverable reserve of coal resources in the mining area, and the recoverable reserve of coal is the basis for determining the reasonable scale of mining. China is the world’s largest coal producer, with coal reserves ranking the third in the world (Zhang et al., 2010; Xie, 2012). However, China has an uneven distribution of coal reserves, i.e., more coal resources are distributed in the west while less in the east. Due to the fragile ecological environment and the imbalanced distribution of coal resources and water resources, China suffers from a great difficulty in coal exploiting. Therefore, it is necessary to determine a reasonable mining scale in the western mining areas of China.

2) Market demand is an important factor affecting coal mining scale. The interdependence between market demand and coal mining scale affects the supply-demand balance of coal market and restricts the development of coal market (Horbach et al., 2014; Li, 2017). When the coal mining scale exceeds the market demand, it will lead to decreased coal prices, declined corporate profits, and weakened ability of enterprises in controlling the water resources. When the coal mining scale is less than the market demand, there will be a shortage of supply. This is beneficial from the perspective of enterprises as the coal price will rise and the scale and efficiency of coal mining will be increased. However, this is not conducive to the development of the coal market in the long run, because the temptation of high coal price will promote large-scale production, resulting in oversupply (Rademacher, 2008). A reasonable scale of coal mining can only be determined by reaching a balance between market demand and coal mining scale.

3) Mining condition is one of the main constraints on the scale of coal mining. A complex mining condition will inevitably bring difficulty in mining (Wang, 2014). In deep mining, mine disasters such as coal burst, coal and gas outburst, coal seam water inrush occur easily. In the process of shallow mining, ecological problems such as deterioration of surface ecology and loss of water resources occur frequently (Zhu, 2011). In addition, mining equipment is also an important factor affecting the mining scale.

4) The deterioration of ecological environment is the secondary disaster caused by coal mining (Wei, 2010). High-intensity coal mining will inevitably lead to the deterioration of ecological environment. The

scale of coal mining must be determined by considering the ecological environment and the WRCC. There is a dynamic mutual exclusion between coal mining and ecological environment, in which three states and a critical point exist (Wu et al., 2009; Du and Chen, 2014). In the first state, coal mining intensity is not strong enough to break the ecological balance, or some damages are caused by coal mining but quickly restored under the effect of the ecosystem's self-repair ability. In the second state, coal mining brings disastrous consequences to the ecological environment, and the ecological balance is seriously damaged. In the last state, coal mining and ecological environment reach a perfect balance (Zhang et al., 2010; Li, 2017). In order to achieve sustainable development of coal industry, it is necessary to obtain a reasonable mining scale so as to maintain a perfect balance between ecological environment and coal mining.

5) Safety and efficiency of coal mining. Personal safety should be placed in the first place, followed by the exploitation rate of resources (Xie, 2012). The aim of safe mining is to reduce the occurrence rate of coal mine accidents and occupational diseases of mining workers. The connotation of efficient mining refers to introducing informatization, mechanization and intellectualization into the coal mining (Xie, 2012; Dzonzi-Undi and Li, 2016). Safety and efficiency are two basic requirements of coal mining. Reducing safety accidents and the death rate per ton of coal is the top priority in current China's coal mining industry. Realizing efficient coal mining is the goal of many coal enterprises. In conclusion, safety and efficiency are important factors affecting the scale of coal mining (Geng and Saleh, 2015).

6) Mining cost is a key factor affecting the scale of coal mining. Mining cost is related to the payment items, such as environmental governance cost, workers' remuneration, etc (Li, 2017). Different mining methods have different mechanization levels and induce different mining costs. The improvement and reform of mining methods will affect the coal mining scale in the way of mining cost.

7) Efficiency is a key factor that enterprises will attach importance to. In pursuit of maximum benefits, enterprises should take into account the coordinated development of mining scale, ecological environment and water resources comprehensively (Rademacher, 2008; Wu et al., 2009; Horbach et al., 2014). Especially in ecologically fragile mining areas, the coal mining scale must conform to the technical measures and local geological conditions. Pursuing interests but neglecting environment protection is an unsustainable development mode, which no long meets the needs of the present age.

8) WRCC is a constraint on the scale of coal mining as well as a basic condition for realizing green mining and ecological environmental protection in mining areas (Chi et al., 2019). Water resources are easily damaged by coal mining (Obiadi et al., 2016; Adiansyah et al., 2017). Water resource is one of the most important factors that should be considered in coal mining in ecologically fragile mining areas, because the change of water resources directly affects the regional ecological environment (Bian et al., 2009). In recent years, people from all walks of life have increasingly higher demand on the ecological environment. To realize the balance between coal mining and ecological environment, the key method is to measure the coal mining scale using WRCC as the constraint.

These influencing factors are interrelated. When the influence degree of one factor on the mining scale changes, it will cause other factors to change. For example, when the water resources carrying capacity decreases, it will lead to the deterioration of the ecological environment, which will affect the coal mining volume, reduce the benefit and change the market demand. Generally speaking, coal resource reserves, market demand and the benefits from the development of coal resources determine the mining conditions, safety and efficiency, and the mining costs of coal enterprises, thus affecting the mining scale. The coal reserves, mining conditions, safety and efficiency, mining costs and other internal conditions determine whether the coal production can meet the market demand. The ecological environment and the water resources carrying capacity are the external constraints of coal resource reserves, mining conditions, safety and efficiency, mining costs, market demand and benefits, which also affect coal mining scale. In summary, mining conditions, safety and efficiency of mining, mining costs restrict the coal output, and indirectly restrict the market demand. The coal output required by the market determines the mining scale. Under the constraints of ecological environment and water resources carrying capacity, the mining scale is limited, which will affect the market demand. For ecologically fragile mining areas, it is necessary to comprehensively consider multiple factors, so as to realize scientific mining, environmental protection and sustainable development simultaneously.

3. Dynamic decision model of coal mining scale under WRCC constraint

3.1. The decision model of coal mining scale

In the previous research on the scale of coal mining, most models are established based on either the production side or the market demand side, but very few are based on the combination of the two, which is unfavorable to the decision-making of coal mining scale. Therefore, it is necessary to consider the factors from production side, demand side and external restraint side comprehensively. The main influencing factors of mining scale can be divided into three categories. The first category of influence factors from production side include coal reserves, mining conditions, safety and efficiency of mining, mining costs; the second category of influence factors from the demand side include market demand and benefits; the third category from the external constraint side include ecological environment and WRCC. The three categories of influence factors coordinate and restrict with each other, and jointly decide the scale of coal mining. The relationship among the three is shown in Fig. 1.

It can be seen from Fig. 1 that the decision-making result of coal mining scale is jointly determined by the three categories of factors. The production side restricts how much coal can be produced, which is a constraint on market demand; the amount of coal required on the demand side determines how much coal a coal enterprise needs to produce. A reasonable coal output of an enterprise and a perfect balance between supply and demand determines the healthy development of the coal market (Mohr et al., 2011). However, this situation does not consider the balance between the changes in external conditions brought about by coal mining. In fact, considering the factors from constraint side, the mining scale of the mining area needs to be re-planned. Due to the difference in mining method and geological condition, the changes of WRCC and ecological environment are also uncertain. The traditional planning method has limited prediction capacity, because the three categories of influencing factors change with time and change with each other. In order to obtain a reasonable scale of coal mining, it is necessary to make decision by considering dynamic change of all three categories of factors, which basically entails the optimal control theory. The optimal control theory is based on the dynamic programming and maximum value theory proposed by R. e. bellman and Pontryagin et al. (Fletcher, 2017), and its basic idea is to solve an index under a certain initial condition. The performance index is optimal when it is transferred to the specified target state. In fact, the problem of determining coal mining scale under the constraint of the three categories of factors is a dynamic programming problem, which can be solved by the optimal control theory. The Hamilton-Jacobi-Bellman (*H-J-B*) equation proposed by Hamilton et al. can be used to analyze the optimal control theory very well (Monovich and Margaliot, 2011; Hawkes, 2017; Kim and Kraft, 2017; Baek et al., 2018; Kurogi, 2018; Neto et al., 2018).

3.2. Decision-making process of coal mining scale under the constraint of WRCC

Profit maximization is one of the goals pursued by enterprises. By regarding the profit of coal enterprises as an objective function and taking the main influencing factors as the constraints, the decision-making of mining scale was discussed in this paper. The purpose of determining a reasonable scale of coal mining in an ecologically fragile mining area is not only to maximize the benefits of enterprises (maximum coal output) and minimize water resources damage, but also to seek the balance between coal mining and ecological environment. Generally, a better state of WRCC allows a larger coal mining scale, and thus a greater enterprise profit can be achieved. The profit balance equation of coal mining under the constraint of WRCC is established as follow.

$$M(t) = P_t Q_t - C_1(Q_t, \beta_t) \tag{1}$$

where M(t) is the total profit of coal sold within t time; Q_t is the scale of coal mining within t time; P_t is the price of coal within t time; $C_1(Q_t,\beta_t)$ is the cost of mining within t time, β_t is the management cost induced by the decline of WRCC within t time.

In formula (1), the main factors influencing mining scale are coal resource reserves, mining cost, WRCC and market demand. The specific impact of each factor is as follows:

1) *Coal reserve.* The coal reserve is a variable quantity, which will increase with the increase of exploration amount and decrease with the increase of mining amount. The total amount of coal reserve is equal to the increment of exploration amount minus the increment of mining amount. In this paper, the relationship between coal reserve and mining scale was established, and the reduction amount of coal reserves was obtained according to formula (2). At the same time, coal reserves conform to geometric Brownian motion, so the constraint equation can be obtained as formula (3) according to the results of Li (2017):

$$\begin{cases} S_{t+1} - S_t = -Q_t(t = 0, 1, 2, \cdots T-1) \\ S_0 = S(0)\text{Initial reserves} \end{cases} \tag{2}$$

$$dS = -Qdt + \alpha S dt + \delta_1 S dz_1 \tag{3}$$

where S is the reserve of coal resources ; S_t is coal reserve at t-moment; S_{t+1} is coal reserve at t+1 moment; S_0 is the coal reserve at initial moment; dS is the change of coal reserves during a certain time interval; dt is time interval. $T \in [0,t]$, T is the mining life, Z_2 follows the Wiener process and satisfies $z_1 = \varepsilon_1 \sqrt{dt}$. ε_1 is a random value which obeys the standard normal distribution. α is the expected average of annual change rate of coal reserves, and δ_1 represents the volatility of coal reserves.

2) *Coal price.* In order to maximize profits, enterprises will adjust the mining scale according to the coal price fluctuation. According to the results of previous research, the coal price accords with geometric Brownian motion. The mathematical model equation is shown as formula (4):

$$dP_t = \mu_1 P_t dt + \sigma_1 P_t d\omega_{t1} \tag{4}$$

where P_t is the coal price; ω_t is the Wiener process; μ_1 is the expected growth rate of coal price; σ_1 is the price volatility of coal.

3) *Mining cost.* Mining cost refers to the cost per ton of coal. In this paper, the safety cost, efficient mining cost, infrastructure cost, mining process cost are all regarded as the mining cost. At the same time, the restoration cost of water resources damage caused by coal mining is regarded as additional cost. When the exploitation destroys the water resources and leads to the deterioration of the ecological environment, the additional cost is the decline of WRCC. Previous research has shown that C_1 (Q_t) and coal mining scale Q_t conform to quadratic functions. The mining cost model expression is shown as formula (5):

$$C(Q_{t+1}, \beta_{t+1}) = AQ_t^2 + BQ_t + CB_t + D \tag{5}$$

where a, b, c and d are constants; B_t is a function of β_t and Q_t, indicating the relationship between β_t and Q_t.

4) *Additional cost incurred by the decline of WRCC.* Coal mining leads to the decline of WRCC, resulting in the damage of ecological environment. In order to ensure the benign development of the ecological environment in the mining area, it is necessary to protect the water resources and the ecological environment. By changing the mining method, the WRCC in the mining area can be restored to the threshold value, so that a dynamic balance state of development can be achieved. As shown in formula (6), $\bar{\beta}$ is the threshold value of support capacity of WRCC in the mining area to the ecological environment under the mining effect, and the critical value (0.6) between serious overload (V) and slight overload (IV) is taken as the evaluation threshold.

$$C(\beta_t) = \begin{cases} C(\beta_t)\text{When}\beta_t < \bar{\beta} \\ 0\,When\beta_t > \bar{\beta} \end{cases} \tag{6}$$

When the WRCC decreases, the coal cost per ton increases, which is due to that enterprises need to pay for restoration. By referring to the relationship between ecological compensation and mining cost (the United States and other countries believe that the cost of producing one ton of coal needs to be increased by X Yuan, and the relationship between ecological compensation and mining cost is linear), this paper assumes that the relationship between WRCC and mining scale is expressed as formula (7), and the WRCC is expressed as formula (7). When the WRCC decreases by 0.1, the cost per ton of added coal is θ, and θ is a constant

$$B_t = \theta \beta_t Q_t \tag{7}$$

Then formula (5) can be expressed as:

$$C(Q_{t+1}, \beta_{t+1}) = AQ_t^2 + BQ_t + \kappa \beta_t Q_t + D \tag{8}$$

where $\theta = C{\cdot}\kappa.\kappa$ is a constant, which represents the relationship between the additional cost and the total cost after the decline of WRCC.

5) *Market demand.* Market demand is an important index affecting the scale of coal mining. Relevant research has shown that there is an inverse function relationship between market demand and coal price. The coal market demand can be obtained by formula (9), where D_t represents the coal market demand.

$$\begin{cases} D_t = \dfrac{dD_t}{dP_t} < 0 \\ D_0 = D(0) \end{cases} \tag{9}$$

Under market competition, coal resources are continuously mined within time T. T represents the mining life of coal resources, which can be divided into T stages [0,1], [1,2] … [T-1,t]. At the end of t year, the mine revenue is defined as $M(t) = P_tQ_t - C_1(Q_t, \beta_t)$, and the profit maximization of coal mining during the mining period is taken as the objective function. Based on the research results of coal reserves and mining cost, the optimization model of mining scale under the constraint of WRCC was constructed, as shown in formula (10):

$$\max V = \sum_{t=1}^{T} (P_t Q_t - C_1(Q_t, \beta_t)) \bullet \rho^t \tag{10}$$

where $\rho = \frac{1}{1+r}$, r is the discount rate, and formula (10) satisfies the constraints in formula (2).

Through construction and interpretation of the constraint equation of each factor, the influences of factors were measured. The Lagrange function was constructed based on the objective function:

$$\begin{aligned} L &= \sum_{t=1}^{T} (P_t Q_t - C_1(Q_t, \beta_t)) \bullet \rho^t + \sum_{t=0}^{T-1} \lambda_t(-Q_t + S_t - S_{t+1}) \\ &= \sum_{t=0}^{T-1} \left[\rho^{t+1}(P_{t+1}Q_{t+1} - C_1(Q_{t+1}, \beta_{t+1})) + \lambda_t(-Q_t + S_t - S_{t+1})\right] \end{aligned} \tag{11}$$

Since the potential function is unknown in formula (11), the mining scale is unknown and the final multi-solution phenomenon occurs. Therefore, the Hamilton function $H(\cdot)$ is introduced.

$$H(\cdot) = P_{t+1}Q_{t+1} - C_1(Q_{t+1},\beta_{t+1}) - \frac{\lambda_t Q_t}{\rho^{t+1}} = H(Q_{t+1}, S_t, \lambda_{t+1}, t) \tag{12}$$

The Lagrange function can be expressed as:

$$L = \sum_{t=0}^{T-1}\left[H(\cdot)\rho^{t+1} + \lambda_t(S_t - S_{t+1})\right] \tag{13}$$

The mining scale, coal reserves and potential function were derived, respectively.

$$\begin{cases} \dfrac{\partial L}{\partial Q_t} = \rho^{t+1}(P_{t+1} - C'(Q_{t+1},\beta_{t+1})) - \lambda_t = 0 \\ \dfrac{\partial L}{\partial S_t} = \lambda_t - \lambda_{t+1} = 0 \\ \dfrac{\partial L}{\partial \lambda_t} = S_t - S_{t+1} - Q_t = 0 \end{cases} \Rightarrow \begin{cases} \rho^{t+1}(P_{t+1} - C'(Q_{t+1},\beta_{t+1})) = \lambda_t \\ \lambda_t = \lambda_{t+1} \\ S_{t+1} - S_t = -Q_t \end{cases} \tag{14}$$

So there is:

$$\rho^{t+1}(P_{t+1} - C'(Q_{t+1},\beta_{t+1})) = \lambda_0 \tag{15}$$

Through substituting formula (15) into formula (8), we can get:

$$\rho^{t+1}(P_{t+1} - 2AQ_{t+1} - B - \kappa\beta_t) = \lambda_0 \tag{16}$$

The relationship among mining scale, coal price and WRCC can be obtained:

$$Q_t = \frac{(P_t - B - \kappa\beta_t) - \frac{\lambda_0}{\rho^t}}{2A} \tag{17}$$

It can be seen that only λ_0 is an unknown solution in the process of coal mining. The boundary condition $S_0 = S(0)$ can be obtained by $\sum_{t=0}^{T-1} Q_t = S(0)$. By substituting into formula (17), there is:

$$\sum_{t=0}^{T-1} \frac{(P_t - B - \kappa\beta_t) - \frac{\lambda_0}{\rho^t}}{2A} = S(0) \tag{18}$$

The general solution of λ_0 can be obtained:

$$\lambda_0^* = \frac{\sum_{t=0}^{T-1}(P_t - B - \kappa\beta_t) - 2AS(0)}{\sum \rho^{-t}} \tag{19}$$

By substituting it into formula (17), the expression of coal mining scale under the constraint of WRCC can be obtained.

$$Q_t^* = \frac{1}{2A}\left[(P_t - B - \kappa\beta_t)\rho^t - \frac{\sum_{t=0}^{T-1}(P_t - B - \kappa\beta_t) - 2AS(0)}{\sum_{t=0}^{T-1}\rho^t}\right] \tag{20}$$

The following is a solution to obtain the scale of coal mining under the constraint of market demand:

Suppose the coal market demand satisfies:

$$D_t = aQ_t - bP_t + c \tag{21}$$

where $a, b > 0$.

By substituting it into (17), we can obtain the mining scale equation under the constraint of market demand. Without considering the influence of WRCC and the mining cost incurred by the decline of WRCC, formula (22) can be obtained:

$$\frac{\frac{aQ_t + c - D_t}{b} - B - \frac{\lambda_0}{\rho^t}}{2A} = Q_t \tag{22}$$

Similarly, there is an unknown coefficient λ_0 in this formula, and formula (21) can be transformed into:

$$\frac{aQ_t + c - D_t}{b} - B - \lambda_0\rho^{-t} = 2AQ_t \tag{23}$$

$$\frac{c - D_t}{b} - B - \lambda_0\rho^{-t} = \left(2A - \frac{a}{b}\right)Q_t \tag{24}$$

$$\frac{\frac{c - D_t}{b} - B - \lambda_0\rho^{-t}}{2A - \frac{a}{b}} = Q_t \tag{25}$$

By substituting the constraint condition $\sum Q_t = S(0)$ into (25), there is:

$$\sum\left(\frac{c - D_t}{b} - B\right) - \lambda_0\sum\rho^{t-1} = \left(2A - \frac{a}{b}\right)S(0) \tag{26}$$

To solve the equation, the general solution form of λ_0 can be obtained:

$$\lambda_0^* = \frac{\sum\left(\frac{c-D_t}{b} - B\right) - \left(2A - \frac{a}{b}\right)S(0)}{\sum\rho^{-t}} \tag{27}$$

Finally, the amount of coal mining under the constraint of market demand is:

$$Q_0^* = \frac{1}{2A - \frac{a}{b}}\left[\frac{c - D_t}{b} - B - \lambda_0^*\rho^{-t}\right] \tag{28}$$

The coal mining scale under the constraint of WRCC is different from that under the constraint of market demand. The ecological environment of the mining area plays a dominant role, while the market demand plays a supplementary role. The decision modes are as follows:

1) When $Q_t^* < Q_0^*$, that is, the allowable coal mining scale under the constraint of WRCC is smaller than that under the constraint of

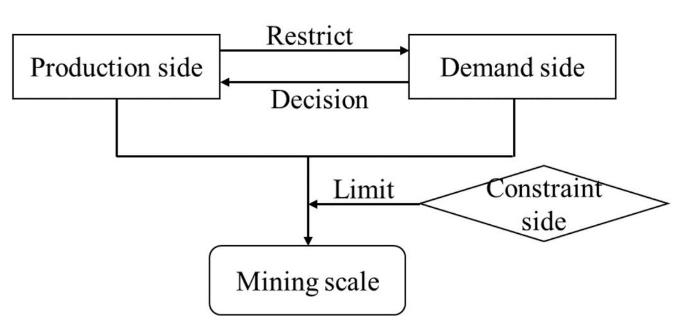

Fig. 1. Relationship between mining scale impact factors.

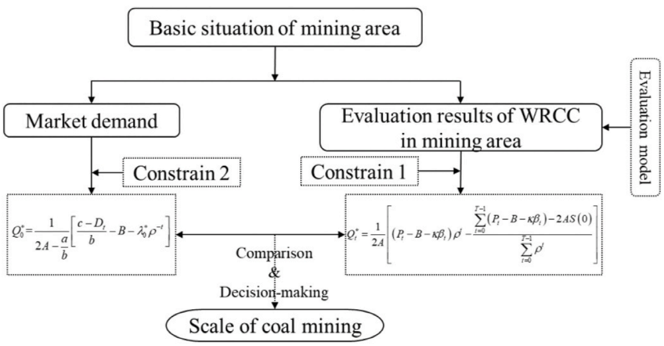

Fig. 2. Flow chart of model solving process.

market demand, and the WRCC in the mining area should be taken as the benchmark. Compared with the mining scale under the constraint of market demand, the priority should be given to the mining scale under the constraint of WRCC, so as to ensure the benign development of ecological environment in the mining area.

2) When $Q_t^* > Q_0^*$, that is, the coal mining scale under the constraint of market demand is smaller than that under the constraint of WRCC, and the coal mining scale under the constraint of market demand does not affect the WRCC and can meet the market demand. In this case, the mining area can be normally mined. However, in order to avoid the phenomenon of "supply exceeding demand", over-exploitation should be prohibited.
3) When $Q_t^* = Q_0^*$, that is, the coal mining scale under the constraint of WRCC is equal to that under the constraint of market demand, and the WRCC is in the boundary state. If the mining scale is too large, it may lead to the deterioration of water resources and ecological environment. In order to ensure the sound development of water resources and ecological environment in the mining area, the scale of coal mining can be reduced appropriately.

In the three cases mentioned above, the decision-making results of mining scale should be made based on the balance between water resources protection and market demand–"water-based mining scale". The decision-making results not only protect the water resources in the ecologically fragile mining area, but also meet the market demand. At the same time, it avoids oversupply and realizes the sustainable development of ecological environment and coal industry in the mining area. The decision-making process of coal mining scale is shown in Fig. 2.

4. Decision of coal mining scale under the constraint of WRCC in Yili mining area

4.1. Analysis of geological conditions and WRCC in Yili mining area

Yili No.4 mine is located in the southeast of Huocheng County, Yili Kazakh Autonomous Prefecture, the Xinjiang Uygur Autonomous Region, with the geographical coordinates of East longitude 80°57′00″-81°11′00″ and North latitude 44°01′00″-44°06′00″. The minefield is 18.74 km long and 9.32 km wide, covering an area of 113.3 km^2. The geographical coordinate of the minefield center is East longitude 81°04′30″ and North latitude 44°03′30″. The location of coal mine is shown in Fig. 3.

The minefield is located in the southern part of Yili basin, which is basically a complete single hydrogeological unit. The terrain is high in the south while low in the north. From south to north, it can be divided into five geomorphic units, namely mountain, hill, inclined plain, terrace plain and floodplain of the Yili River. The minefield lies in the transitional zone between hill and sloping plain. Yili No.4 mine is located in the Yining coal mining area which is north of the Yibei coal field. The mining scale force is designed to be 6 million t/a. Coal seam 21–1 and coal seam 23–2 are mainly mined in the first mining area of the minefield. The recoverable thickness of coal$_{21\text{-}1}$ coal seam is 1.35–8.93 m, with an average value of 5.3 m and buried depth is 100–575 m. In contrast, the recoverable thickness of coal$_{23\text{-}2}$ seam is 2.05–11.5 m, with an average value of 7.73 m and buried depth is 75–525 m.

According to the actual situation of Yili mining area, the WRCC in the mining area is calculated by using the fuzzy comprehensive evaluation method, and the WRCC from 2015 to 2020 is obtained (Table 1). In this paper, the mining scale of the mining area is studied based on the evaluation results of WRCC in Yili mining area and by taking WRCC as the constraint condition. A new mining scale under the constraint of

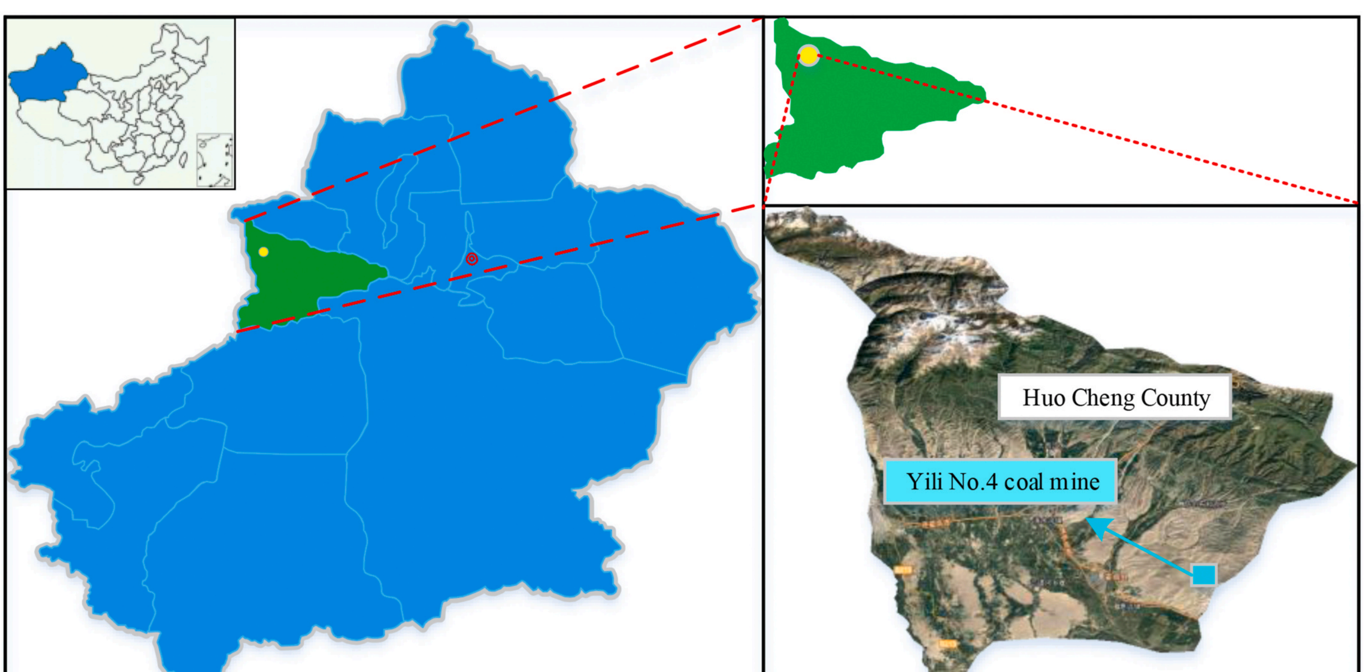

Fig. 3. Location of Yili No.4 mining area.

Table 1
Calculation results of water resources carrying capacity in Yili mining area.

Year	Present year			Forcast year A			Forcast year B		
	2015	2016	2017	2018	2019	2020	2018	2019	2020
Evaluation value of WRCC (β)	0.80	0.74	0.70	0.68	0.60	0.57	0.74	0.74	0.76
Level	II	III	III	IV	V	III	III	III	III

Table 2
2002–2017 China coal development basic situation (Date from China Coal Resources Network).

Year	Demand/ 100 million tons	Price (ton/ yuan)	Production volume/100 million tons	Reserves/ 100 million tons	Prime cost (ton/ yuan)
2002	15.23	252	13.8	3312.0	118
2003	18.06	303	16.7	3354.0	136
2004	20.76	517	19.9	3373.5	170
2005	19.97	415	23.5	3335.5	176
2006	22.50	426	25.3	3340.9	164
2007	20.39	395	26.9	3266.7	166
2008	20.99	740	28.0	3272.2	365
2009	22.82	584	32.4	3183.5	268
2010	25.43	743	34.3	2791.2	274
2011	27.51	850	35.2	2160.1	292
2012	29.82	767	39.5	2310.1	261
2013	36.10	590	39.7	2366.2	224
2014	39.25	518	38.7	2399.9	167
2015	37.27	411	37.5	2440.3	145
2016	36.28	478	34.1	2840.3	183
2017	36.62	644	35.2	3655.3	221

Table 3
Parametric fitting results.

a	b	C	A	B	C
1.0897	−0.0213	5.4452	−0.3729	24.4092	−164.0187

Table 4
Xinjiang Coal price statistics (date from China coal resources network).

Year	2013	2014	2015	2016	2017	Average
Price (yuan/ton)	183.1	180.2	176.1	206.9	241	197.46

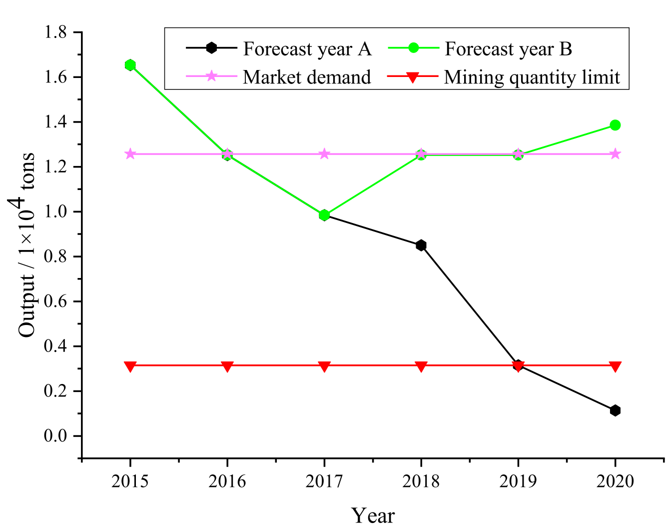

Fig. 4. Calculation results of mining scale under two kinds of WRCC.

WRCC is determined in this study, which meets the needs of both market demand and ecological environment protection.

4.2. Analysis of mining scale in Yili mining area under the constraint of WRCC

In section 3.2, the mining scale under the constraint of WRCC is analyzed based on optimal planning theory. This paper makes statistics on coal-related parameters in China from 2002 to 2017, including coal market demand (replaced by consumption data), coal price, mining amount, coal reserves and mining cost per ton of coal, as shown in Table 2. In the past, the WRCC of mining area was not considered as a constraint condition, so it had no influence on the parameters in the fitting process. formula (8) and (9) were fitted, then the parameters of the two equations were obtained, as shown in Table 3. According to the discount rate in recent years, r is set to 4.0%, and the mining scale is calculated according to the fitting data and the basic conditions of Yili mining area.

According to China Coal Resources Network statistics, the data on Xinjiang coal price in recent years can be obtained, as shown in Table 4. It can be seen that the coal price of Yili No.4 coal mine is ￥197.46.

According to the calculation results of WRCC from 2015 to 2020, the mining scales in the forecast year *A* and *B* are obtained, as shown in Fig. 4. Meanwhile, the mining scale based on the market demand in recent years is obtained. It can be seen that in forecast year *A*, with the decrease of WRCC, the mining scale also gradually decreases. When the WRCC falls below 0.6, the mining scale is lower than the mining limit, and then mining activity is stopped. This indicates that when the WRCC drops to a severely overloaded state, the WRCC will be lost, resulting in serious damage to the ecological environment. In such case, coal mining should be prohibited. When the WRCC is greater than 0.6, the allowable mining scale under the constraint of WRCC is less than that under the constraint of market demand, that is, the market demand cannot be met and the coal mining scale under the constraint of WRCC is in dominant position. In the forecast year *B*, the WRCC exhibits a yearly recovery trend by aquifer-protective mining, and the mining scale under the constraint of WRCC is gradually improved compared with the situation in forecast year *B*. In 2018 and 2019, the allowable mining scale under the constraint of WRCC is basically equal to that under the constraint of market demand. In the year of 2020, with the increase of the WRCC, the mining scale under the constraint of WRCC will exceed that under the constraint of the market demand.

The above analysis shows that WRCC has a great influence on the mining scale. The WRCC in mining area can be improved by implementing aquifer-protective mining and other related measures (Zhang et al., 2011a, 2011b). When the WRCC is at a certain value, the allowable mining scale can meet or exceed the coal market demand. The market demand can also be regarded as a constraint to promote the market development. The two constraints restrict each other, which ensures the protection of water resources and ecological environment in the mining area and avoids coal market disorder induced by overproduction. As can be seen in Fig. 4, when the WRCC falls below 0.6, a small scale of coal mining is allowed and the WRCC is lost. In such case, the damage of the ecological environment will be huge and irreversible and the production of coal must be stopped. In fact, when the allowable scale of coal mining under the constraint of WRCC is close to the lower limit of mining scale, or when the WRCC declines continuously, coal

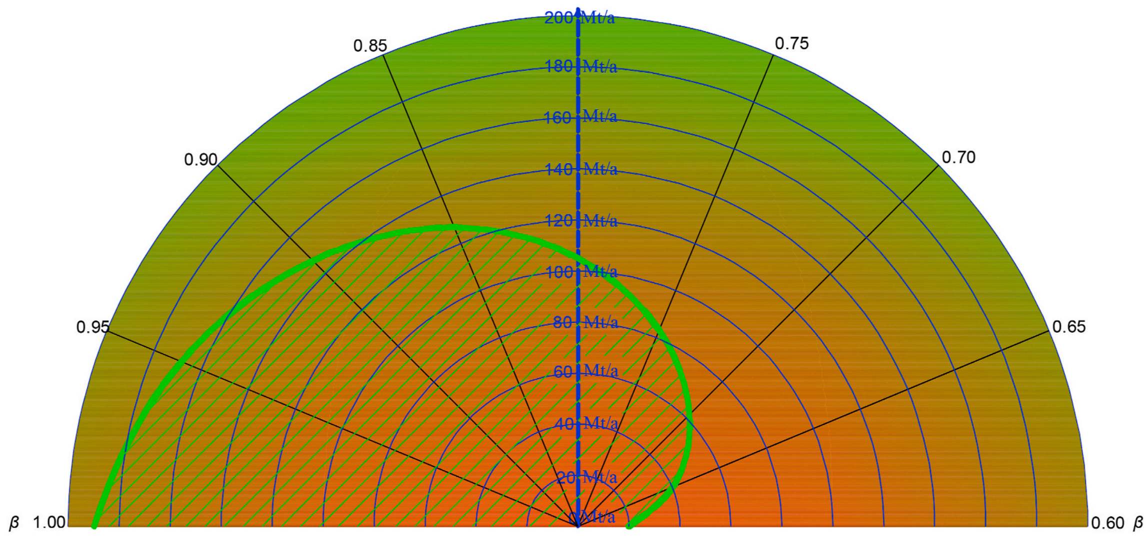

Fig. 5. Illustration of mining scale under different WRCC in Yining mining area.

mining will cause great damage to water resources, resulting in deterioration of the ecological environment in the mining area. Consequently, corresponding artificial optimization measures should be taken to maintain the WRCC in the mining area.

Based on the above analysis results, according to the mining concept of "water-based mining scale " and the actual situation of Yili mining area, the mining scale corresponding to different states of WRCC is determined. As shown in the green curve range in Fig. 5, with the decrease of WRCC, the mining scale gradually decreases. When the WRCC drops to 0.6, the maximum allowable mining scale in the mining area is 19.26Mt/a. At this time, the supporting capacity of water resources to the ecological environment is in a state of deficit, and the damage of coal mining to the ecological environment is fatal and irrecoverable. When the WRCC rises to 0.7–0.79, the allowable mining scale in the mining area is 61.89–100.25Mt/a. At this time, the mining-induced damage to water resources and ecological environment is within the controllable range. When the WRCC is greater than 0.79, the mining scale under the constraint of WRCC is between 104.51 and 189.77Mt/a. Under the constraint of WRCC, the coordinated development between coal mining and ecological environment can not only ensure the sound development of ecological environment, but also ensure the balance of supply and demand in the market.

5. Results and discussion

The mining scale under the constraint of WRCC was analyzed in this paper. Considering the influencing factors from production side, demand side and constraint side, a decision-making model of mining scale was constructed. On the basis of the optimal control theory, the scientific mining scale model of "water-based mining scale" was put forward. The analysis results show that the implementation of water conservation mining can not only protect the ecological environment in the mining area, but also guarantee an ideal mining scale. The extensive mining mode brings damages to the ecological environment and eventually affects the mining scale. Dialectically speaking, a reasonable mining scale is not only friendly to the eco-environment, but also conductive to the realization of coordinated development of society, economy, ecology and enterprises.

Many scholars have done a lot of work on the planning and design of mining scale, which can be categorized into two types. The first type is to plan and design according to the coal reserves in the mining area and formulate the corresponding service life based on the geological conditions and mining methods in the mining area. Most of current researchers are concentrated on prediction and analysis of the total production capacity of a certain country or region so as to obtain the change trend of regional coal production. For example, some scholars think that China's coal production capacity level can reach 1.495–1.63 billion t/a by 2030 and the annual production capacity level can be improved by about 3.0–3.5 billion t/a by 2050, but there is a big gap between the estimated values and the actual mining scale (Xie, 2012; Qian, 2018). Some scholars put forward the corresponding prediction curve and calculation model according to the coal mining scale, and developed the quantitative prediction index and method (Morrison and Catherine, 1985; Zhang et al., 2011a, 2011b). These studies mainly focus on coal reserves rather than other factors, and think that the coal reserve level and geological endowment pattern of coal resources directly determine the long-term production capacity of coal resources (Boyan, 2007; Rodríguez, 2008).

The second type is to adjust the mining scale according to the market supply and demand so as to reach supply-demand balance, which is also called "production to demand". For example, Mohr et al. (2009 and 2011) predicted and analyzed the mining scale of Australia and other countries, and obtained the corresponding prediction results of mining scale. Suwala et al. (2002) studied the transformation and regional adjustment mode of polish coal market and proposed corresponding measures. Andrews-Speed et al. (2003) analyzed the production capacities of small coal mines in China, and put forward the main influencing factors. In fact, the market demand and the coal mining scale are mutually restricted. Kulshreshtha et al. (2001) believed that increasing market demand could expand the scale of coal production but would inhibit the improvement of production efficiency of coal industry. Wang et al. (2011) pointed out that economic growth was an important factor driving the annual growth of coal output. This decision on mining scale only takes into account the market demand, which will easily lead to overcapacity in the actual production process, resulting in "high-risk, high-pollution, extensive and disorderly" coal production (Danicic et al., 2009).

On the one hand, these two types of decision-making methods will lead to the waste of coal resources and the destruction of ecological environment; on the other hand, they will lead to the oversupply and overcapacity of coal production (Korpås, 2007; Kirsch, 2010; Qian, 2018). For ecologically fragile regions, water resource is one of the most precious resources, which is also the bottleneck restricting the development and utilization of coal resources. Once the coal mining leads to the destruction of water resources and ecological environment (Obiadi et al., 2016; Papendiek, 2016), the "ecological loss" will be much greater than the economic value created by the exploitation and utilization of coal resources. Therefore, determining a rational mining scale under the constraint of water resources and ecological environment protection is the basis for the sustainable development of ecologically fragile mining areas. Considering the endowment status of coal resources and the market supply and demand, the mining scale was studied under the constraint of WRCC in this study, which provides a basis for the research of new development planning and mining theory under the constraint of WRCC.

The decision-making of mining scale under the constraint of WRCC is basically to put the ecological environment in the first place and the market demand in the second place. The purpose of this decision-making mechanism is to ensure that water resources will not be over-disturbed by coal mining. In this paper, the optimal control theory is introduced into the decision-making of mining scale, which can well balance the production side and the constraint side. Through case study, it can be known that the mining scale under the constraint of WRCC has its limit, that is, the coal mining will be prohibited when the WRCC is reduced to a certain value. In addition, the decision-making of mining scale should be carried out based on the evaluation system of WRCC. By combining the decision result with the water resources carrying capacity evaluation system, the systematic analysis method integrating the evaluation and decision is realized.

The optimal control theory was introduced in the selection of evaluation methods. Based on H-J-B equation, a mining scale model with WRCC and market demand as constraints was obtained. It is worth noting that this paper only considers main factors but ignores the low-priority factors such as social economic efficiency and policy influence.

6. Conclusions

In view of the fact that the theories and researches of scientific mining scale are still incomplete, this paper studies the scientific mining scale in an ecologically fragile mining area under the constraint of WRCC, and the following conclusions are obtained:

In this paper, the factors affecting the mining scale of ecologically fragile mining areas are analyzed. The factors are mutually related and restrict each other, which have a joint influence on the mining scale. The production side, demand side and constraint side are considered comprehensively as the different factors, and a "three–in-one" decision-making model of mining scale is established to improve the decision-making system of mining scale in ecologically fragile mining areas. On this basis, two kinds of mining scale planning equations with market demand and WRCC as constraints are obtained using optimal control theory, and the scientific mining mode of "water-based mining scale" is put forward.

This paper takes the Yili mining area as an example, and predicts the scale of coal mining from 2015 to 2020 based on the "water-based mining scale" decision model. The results show that the scientific and reasonable mining scale can only be obtained by comprehensively considering the production side, the demand side and the constraint side. In order to ensure the benign development of the ecological environment in the mining area, the WRCC should be taken into account. The allowable maximum mining scale should be reasonably planned. In order to avoid the overexploit and oversupply, coal mining shall be conducted according to the market demand under the restriction of WRCC. When the WRCC is in the boundary state, the mining scale can be appropriately reduced to ensure the sound development of water resources and ecological environment in the mining area.

Determining an optimal mining scale is a frontier scientific issue. This paper studies such issue by computing methods considering multiple factors, with the aim of providing a theoretical basis for actual coal mining.

Author contributions

Mingbo Chi, Conceptualization, Methodology, Data curation, Calculation, Investigation, Writing - original draft. Validation, Formal analysis, Data Formal analysis, Formula derivation, Writing - review & editing. Dongsheng Zhang, Validation, Formal analysis, Data Formal analysis. Wei Yu, Validation, Formal analysis, Data Formal analysis. Resources, Writing - review & editing, Supervision, Data curation. Writing: Writing - review & editing. Qiang Zhao Formula derivation, Writing - review & editing, Data curation, Resources, Writing - review & editing, Supervision, Data curation. Shuaishuai Liang, Writing - review & editing.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

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