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Influencing Factors and Assessment of Coordinated Coal-Water Co-Mining in Ecologically Fragile Areas

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Abstract:

Mu Us Sandland is characterized by dry climate, shortage of water resources and fragile ecological environment, which is extremely sensitive to various human disturbances. However, since it is rich in coal resources, the exploitation of coal resources will inevitably increase the burden on the local environment, resulting in the deterioration of the ecological environment in the mining area. The purpose of this paper is to identify the main influencing factors and their importance of coal-water coordinated co-mining in Jinggong Coal Mine in Mu Us Sandland, and to provide reference for solving the contradiction between coal resources development and ecological environment protection in ecologically fragile areas. Firstly, a research method of influencing factors of coal-water coordinated co-mining based on the full life cycle theory is proposed, in which the coal mine development cycle is divided into three stages according to the disturbance degree of coal mining to the groundwater system and the ecological mutual feedback effect caused by it, combined with the ecological environment characteristics of the mining area, and on this basis, the influencing characteristics of each stage are summarized and a dynamic index database is established. Then, the dependence, feedback and dominance relations among indicators in each stage are distinguished, and cone-bottom elements and cone-top elements are divided. Next, based on Cone-ANP, an analysis model is constructed, and cone element sets in different stages are established, which are used to calculate the weight distribution of each influencing factor. The results show that the geological system in the planning and design stage has a great influence on the coal-water coordinated co-mining, the mining system in the construction and mining stage has become the main influencing factor, and the eco-environment system in the closing and renovating stage has the greatest impact on the co-mining, all of which provide a reference for the improvement of the comprehensive benefits of coordinated co-mining and the improvement of mining technology in the ecologically fragile mining areas in the west.

Keywords: *Ecologically fragile areas, Mu Us Sandland, Coordinated mining of coal and water, Full life cycle theory, Cone-ANP*

I. INTRODUCTION

Although coal resources play a pivotal role in China's national economic development and social progress, coal mining has also caused serious damage to the ecological system of coal mining areas[1], and the ecological environment in coal mining areas has become a major constraint on the sustainable development of mining areas and even regions[2-3]. In China, coal resources are more in the northwest and less in the southeast, which is inversely distributed with water resources[4]. In 2020, the output of raw coal in Northwest China accounted for about 60% of the whole country, while the water resources only accounted for 3.9% of the whole country. Large-scale and high-intensity mining of coal mines will inevitably cause disturbance to water resources, ecological environment, coal-water occurrence relationship and geological structure around the mining area[5], and at the same time, it will cause surface ecological damage, groundwater system damage, land subsidence, etc. [6], which will aggravate the negative effects of ecological environment such as evolution to xerophytic vegetation, soil desertification or salinization[7]. Therefore, in view of the present situation of water resources shortage and ecological fragility in the northwest mining area, it is an important scientific and technological problem to explore the green mining technology in coal mines, pay attention to the research on the utilization of mine water resources, change the thinking from "aquifer protection" to "water resources protection", minimize the impact of mining activities on the ecological environment, and realize the coordinated mining of coal resources and water resources[8].

With the increasing awareness of environmental protection, under the guidance of the concepts of green mining[9-10], "water resources preservation during mining"[11], precision mining[12] and ecological detraction mining[13], relevant scholars have carried out fruitful research and discussion on the mining area development and design, mining technology and methods, ecological environment monitoring and restoration, etc. Qian Minggao and Xu Jialin, et al. systematically expounded the technical framework system of green mining in coal mines based on the concept of green development. Cao Zhiguo et al. conducted physical simulation experiments of coordinated coal-water mining under various special ecological and geological conditions, and proposed that the construction of artificial water-resisting layers at key parts could effectively block the infiltration of overlying aquifer water into mined-out areas[14]. Zhang Jianmin et al. integrated the traditional mining system with the ecological system to construct an analysis model of ecological damage and green mining to quantitatively evaluate the level and effect of green mining[15]. Due to the complexity of many factors, such as natural conditions, occurrence characteristics of water resources, geological system of coal seams in mining areas, mining methods and the degree of disturbance of mining on the surrounding environment, a systematic and effective evaluation system for coal-water green development has not been formed in China at present, but with the defects of imperfect evaluation indexes, low quantification degree of evaluation indexes, and no real-time tracking and dynamic adjustment functions. Based on the theory of system engineering and full life cycle, the research scope is focused on Mu Us Sandland with fragile ecological environment, and six influencing factors including geological conditions, natural resources, mining influence, ecological environment, coal mine disaster and social economy are taken into overall consideration, so as to explore the sensitivity of influencing factors of coal-water coordinated co-mining at different stages and clarify their action modes, hoping to provide scientific basis for improving the comprehensive benefits of coal-water co-mining and the improvement of mining technology.

II. RESEARCH AREA

Mu Us Sandland (37°27'-39°22'N, 107°20'-111°30'E) is located at the junction of Inner Mongolia Autonomous Region, Shaanxi Province and Ningxia Hui Autonomous Region (Fig. 1), with an average annual air temperature of 6.0-9.0℃, annual precipitation decreasing from 420mm in the southeast to 250mm in the northwest, annual evaporation of 1,800 -2,500 mm, dryness of 1.5-2.0, prevailing wind direction in the northwest, and average wind speed of 2.1-3.3 m/s. The sandy land inclines from northwest to southeast, with an altitude of 1,000-1,500m, and is dominated by the landform of alternating beam land with beach land and combining sand dunes with meadows. Affected by climate, the vegetation in Mu Us Sandland has obvious zonality, with dry grassland in the east and desert grassland in the west.

Mu Us Sandland is rich in resources and has over 40 mineral resources in 8 categories, including coal, natural gas and oil and so on. Among the 14 large coal bases in the country, Shendong Coal Base and Northern Shaanxi Coal Base partially overlap with Mu Us Sandy Land. The occurrence characteristics of coal resources determine that the exploitation of coal will definitely affect the surface ecology and environment, and will also disturb the groundwater resources. However, Mu Us Sandland is an arid and semi-arid area with a fragile ecological environment, where high-intensity coal mining has triggered a series of ecological and social problems in recent years, such as the destruction and occupation of land resources, the waste of water resources and water environmental pollution, ecological degradation and destruction. In this study, 10 coal mines (see Table I) in different production stages in Mu Us Sandland were selected as examples for analysis, including 3 in planning and design stage, 6 in construction and mining stage and 1 in closing and renovating stage.

TABLE I. Basic information of coal mines

S/N	Coal mines	Scale of construction(Mt/a)	Main coal seam	Coal seam thickness (m)	Status
1	Kekegai coal mine	10	2- coal seam	5.98	Planning and design
2	Dahaize coal mine	15	2- coal seam	6.19	Planning and design
3	Baijiahaizi coal mine	15	3-1 coal seam	6.77	Planning and design
4	Menkeqing coal mine	12	3-1 coal seam	4.75	Construction and mining
5	Hulusu coal mine	13	3-1 coal seam	4.75	Construction and mining
6	Narin River No. 2 coal mine	8	3-1 coal seam	4.65	Construction and mining
7	Muduchaideng coal mine	10	3-1 coal seam	4.5	Construction and mining
8	Bayangol coal mine	4	3-1 coal seam	5.3	Construction and mining
9	Yingpanhao coal mine	12	2-2 coal seam	6.36	Construction and mining
10	Yuyang coal mine	3	3- coal seam	3.5	Closing and renovating

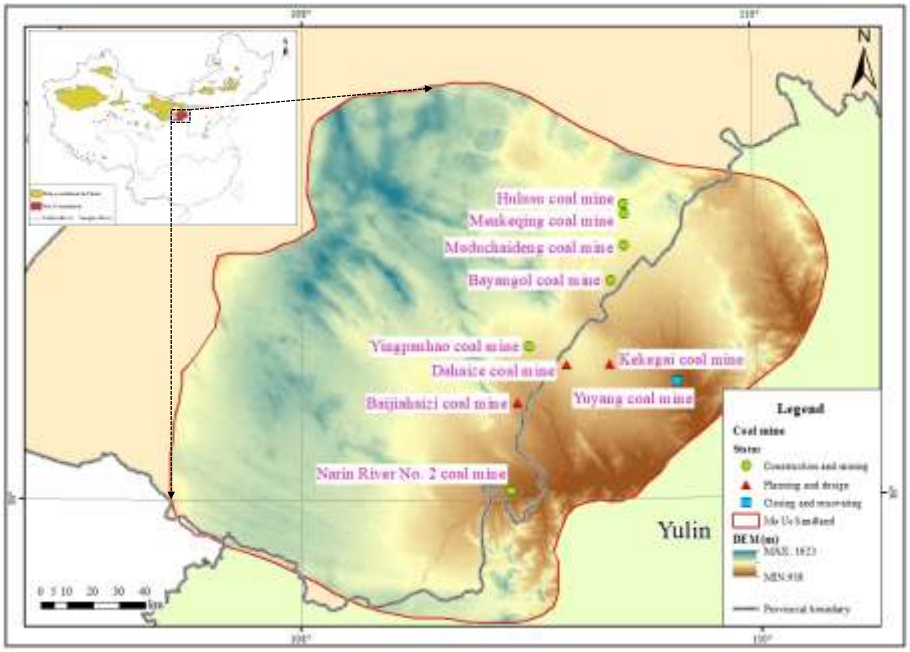


Fig 1: Overview of the research area

III. DIVISION OF COAL MINE LIFE CYCLE STAGES

The non-renewable nature of coal resources determines that the coal mine has a unique life cycle mechanism, that is, the reserves determine the total life cycle length, and the mine life cycle and mining scale will affect the length of each stage in the life cycle. Aiming at the characteristics of various influencing factors and complex interaction relationship in coal-water coordinated co-mining, one-sided attention to a single stage cannot accurately assess the mining benefits. Only by integrating it into the coal mine life cycle and combining the development characteristics of different stages, can the interaction modes among different factors be clarified and the weight distribution of each factor be accurately calculated.

In this paper, according to the special ecological environment characteristics of ecologically fragile mining areas and the different impacts of coal mining on underground water disturbance, the coal mining life cycle is divided into planning and design stage, construction and mining stage and closing and renovating stage.

3.1 Planning and Design Stage

At the planning and design stage, the construction of the mine has not yet started, and the key point of the coordinated coal-water co-mining is to find out the hydrogeological conditions of the coal seam and the key layer, the spatial variation characteristics of water barrier, and to reveal the rock stratum structure of coal mining and the evolution law of mining fissures[16-17]. According to the occurrence relationship of coal water in the ecological vulnerable mining area, combined with the regional ecological environment, geological structure of coal bearing rock series and other characteristics, based on the regional water resource bearing capacity and the principle of regional ecological environment balance, the concept of source ecological detraction mining is implemented, and a scientific and reasonable water resources preservation plan during mining is formulated to realize the coordinated development of coal and water resources and achieve the goal of maximizing social and economic benefits (Fig. 2).

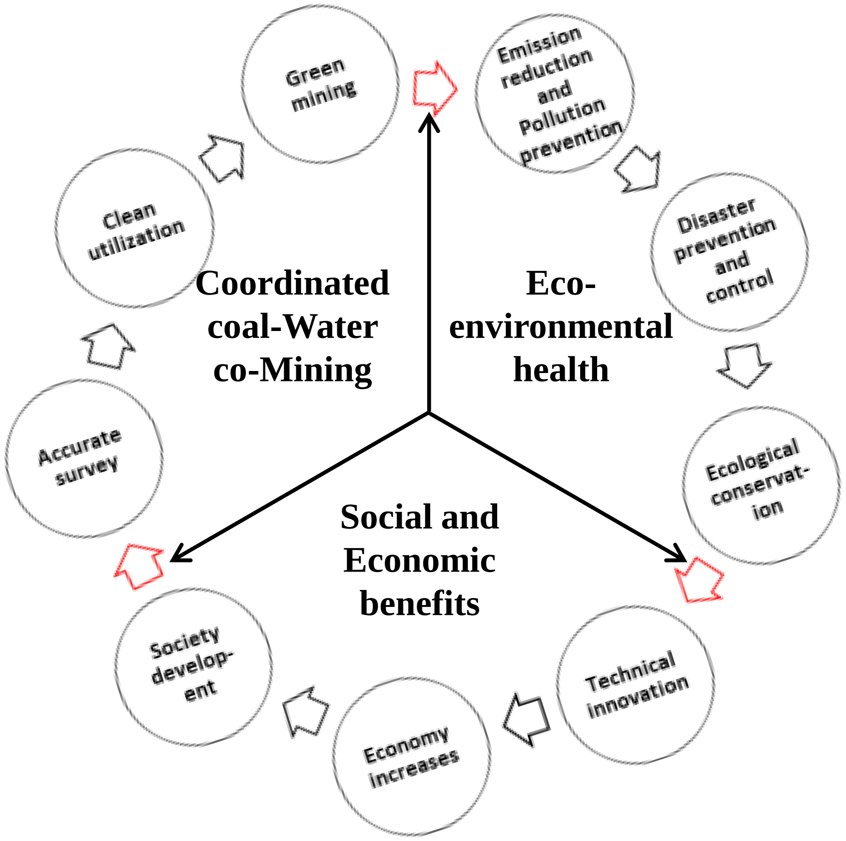


Fig 2: Three-dimensional analysis framework of coal-water co-mining

3.2 Construction and Mining Stage

At the construction and mining stage, three fields (stress field-seepage field-fracture field) are changed under the driving of coal mining. Accurate prediction of mine water inflow and high-efficiency utilization of mine water [18-19] are the key to realize coal-water co-mining. The mining intensity is controlled within the tolerable range of regional ecological environment by comprehensively coordinating the aspects of subsidence reduction mining [20-21], surface ecological detraction mining, solid waste reduction, and mine water treatment and utilization, and changing "post-loss treatment" to "pre-loss prevention" to avoid ecological irreversible damage beyond the ecological self-recovery capability (Fig. 3).

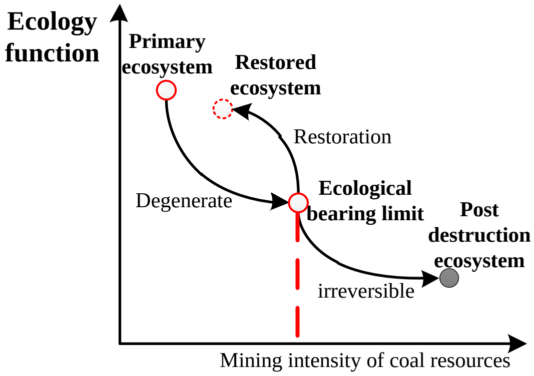


Fig 3: Relationship between mining intensity and ecosystem

3.3 Closing and Renovating Stage

With the withdrawal of coal mining equipment from the mine, the stress environment in the mine, hydrogeological conditions of overlying rocks, environmental quality of groundwater and distribution of heavy metal pollutants will change greatly compared with the original state. Manual intervention and natural recovery should be carried out simultaneously, so as to avoid the possibility of cross-layer pollution of underground water bodies by providing channels for underground liquid (solid) phase wastes to penetrate and leach each other due to the stop of underground drainage and the rise of diving level.

3.4 Factors Affecting Coal-Water Coordinated Co-Mining in Each Stage

The evaluation of coal mining system under the influence of water resources emphasizes the geological occurrence characteristics of coal resources, mining scale and economic and social benefits. Considering the complexity of resources and environmental conditions and the diversity of problems in different regions (mining areas), the green mining technology model adopted has different emphases. For example, for ecologically fragile areas, the assessment of green mining degree focuses on "water resources preservation during mining" and assesses the degree of realization of "water-based production". When constructing the evaluation indicator system of coal-water green development, it is necessary to reflect the comprehensive benefits of green development and carry out all-round evaluation from the aspects of resources, environment and economic benefits.

After consulting the related research on the development and utilization of water resources and energy resources, sustainable utilization evaluation of water resources and water ecological system, literature analysis on coal green mining technology[21-24] and expert consultation, a database of coal-water coordinated co-mining impact factors is established from six aspects including geological system, mining system, natural resources system, ecological environment system, geological disaster system and socio-economic system (Fig. 4). Considering the different requirements of green mining in different stages of coal mines, the influencing factors based on the theory of "full life cycle green mining" also have their own emphasis.

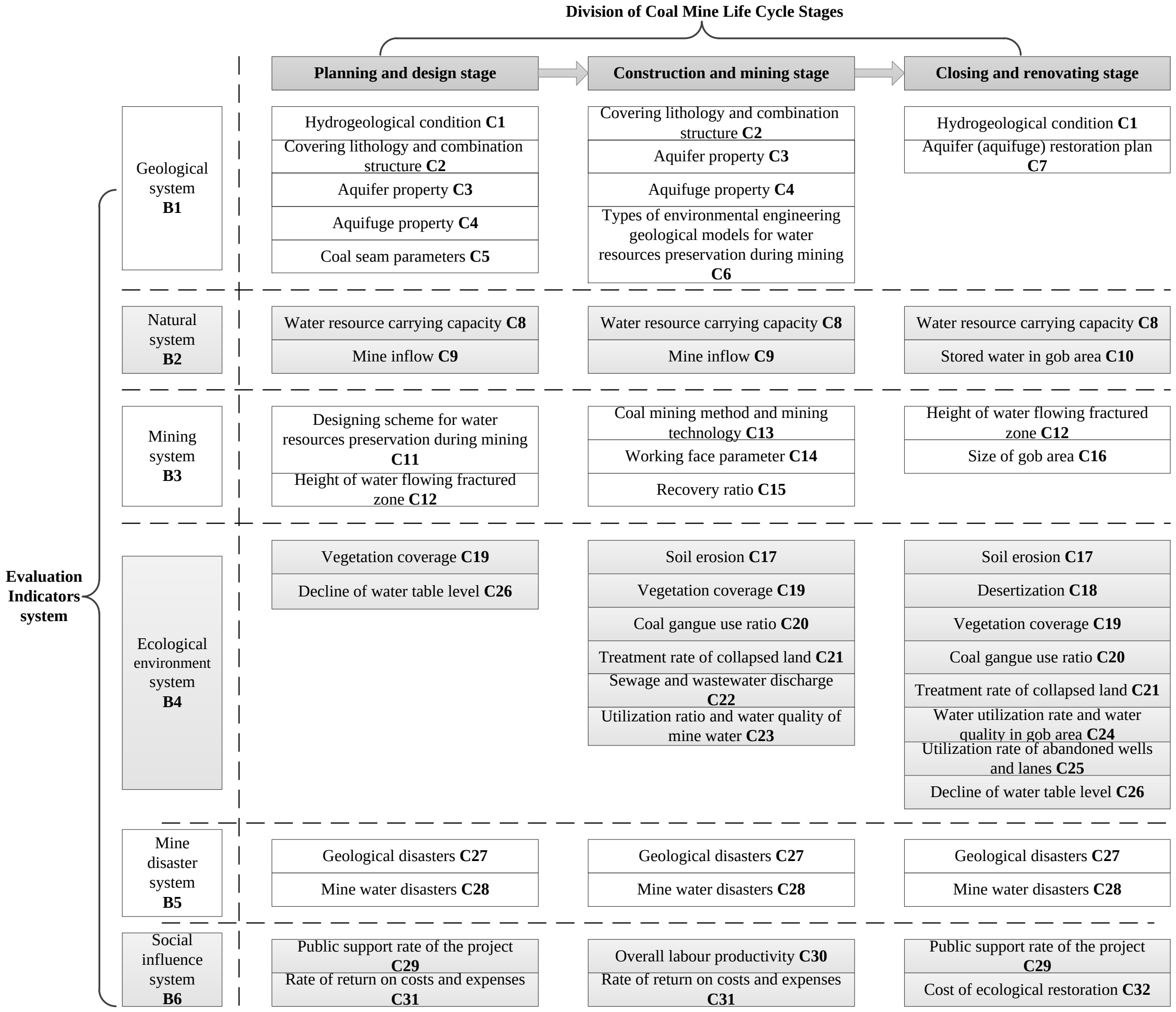


Fig 4: Main influencing factors in different stages of coal-water coordinated co-mining

IV. ESTABLISHING A CONE-ANP MODEL

As the coordinated coal-water co-mining is affected by many factors, based on the full consideration of the correlation of various factors, focus of the paper is laid on grasping the dependence and feedback relationship among the influencing factors of the coordinated coal-water co-mining, paying attention to its origin and transitional characteristics, and weakening the arbitrariness of the subjective judgment of the decision-maker. By using Cone-ANP[22], a Cone-ANP model is constructed to calculate the weight distribution of the influencing factors, and measure the impact on the comprehensive benefit of the coal-water co-mining with the weight distribution of different influencing factors.

4.1 Division of Cone Element Set

Different from traditional ANP elements, pointed cone elements pay more attention to the mutual dominance among elements, so as to divide cone-top elements and cone-bottom elements. The former refers to an element that only has a dominance relation with other elements in this element set and is not dominated by other elements, and is similar to the originating element proposed by Saaty that only the arrow line from it exists in the pointed cone structure, but no arrow line pointing to it, while the latter is dominated by other elements, which can be further divided into "both-in-and-out" transitional cone-bottom elements and "only-in-no-out" receptive cone-bottom elements[23-24] according to the different dominance relations. A pointed cone element set consisting of any number of cone-top elements and cone-bottom elements is called a general pointed cone element set, whose structure is shown in Fig. 5.

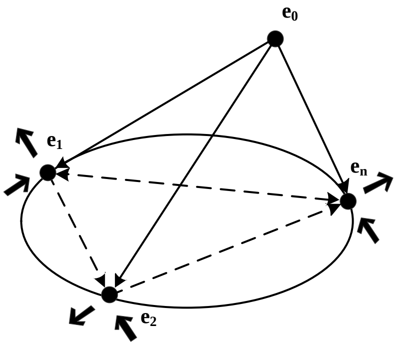
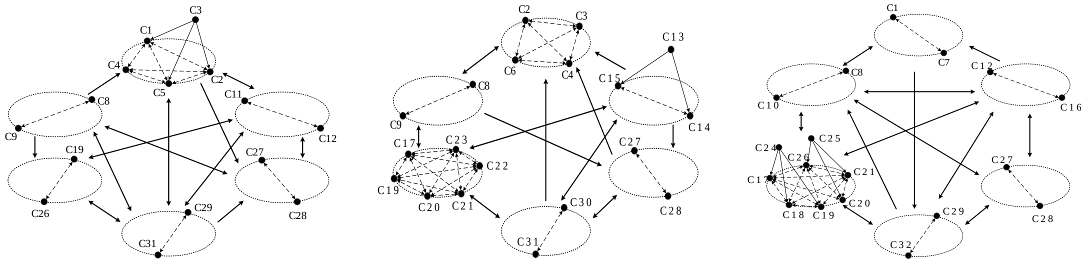


Fig 5: Structure of pointed cone element sets

4.2 Establishing the Cone-ANP Structure for Coal-Water Coordinated Co-Mining

Based on the data collected from typical coal mines in Mu Us Sandland and the characteristics of different development stages of coal mines, the complex dominance relation among the relevant influencing factors in different stages of coordinated coal-water co-mining is determined. An element judgment relationship matrix is established by "0" indicating no direct dominating relationship between the two elements and "1" indicating a direct dominating relationship between the two elements, which further defines the elements at the top and the bottom of the cone in different stages. Meanwhile, the Cone-ANP structure of each stage is established according to the judgment relationship matrix of each stage (Fig. 6). It is obvious from the figure that there is no "only-in-no-out" cone-bottom element in the Cone-ANP structure of each stage.



a Planning and design stage   b Construction and mining stage   c Closing and renovating stage

Fig 6: Structure of Cone-ANP of each stage

V. RESULTS AND DISCUSSIONS

5.1 Calculation of Weights of Influencing Factors

Based on the establishment of Cone-ANP structure for coal-water coordinated co-mining, the weights of the related influencing factors in different stages are calculated. For example, at the closing and renovating stage, the following steps are followed for calculation:

Step I The cone-top element is determined, and the mutual domination and feedback among indicators are comprehensively considered to determine the utilization rate of water quantity and quality in gob area (C24) and the utilization rate of abandoned wells and lanes (C25) at this stage as cone-top elements, and the other 16 influencing factors as cone-bottom elements. The influencing factors are numbered $e_{01}, e_{02}, e_3, \ldots, e_{18}$ (e_{01}, e_{02} are two cone-top elements respectively), and the judgment matrix is constructed. The relative weights β_1 and β_2 of cone-bottom elements in the same cone-top element set relative to different cone-top elements are obtained by using the weight calculation principle of AHP. For all cone-top elements in the cone-top element set, the relative weights of cone-bottom elements of "both-in-and-out" type can be expressed as a preference matrix $\beta_{\mathrm{m}} = \left(\beta_1, \ \beta_2\right)^T$.

Column j (j = 1,2) of the matrix β_{m} indicates the relative weights e_{01}, e_{02} of a cone-bottom element relative to the cone-top element. If all the cone-top elements are regarded as a whole cone-top element e_0, the weight of the cone-top element at time t (t(t=1 1,2, …) can be expressed as:

$$\omega_0^{(t)} = \omega_{01}^{(t)} + \omega_{02}^{(t)} \tag{1}$$

The sum of row i (i=1, 2, …, 16) of the matrix β_{m} indicates the relative weight of a cone-bottom element relative to the cone-top element e_0. β_{m} is summed by rows and normalized to obtain the comprehensive weight of each cone-bottom element relative to the cone-top element:

$$\bar{\beta}_{\mathrm{m}} = (\bar{\beta}_3, \ \bar{\beta}_4, \cdots, \ \bar{\beta}_{18})^T \tag{2}$$

Step II Considering the interaction between different cone bottom elements, if there is a dominance relation between the two cone-bottom elements in the judgment matrix, it is represented by "1" in the judgment matrix. If there is no dominance relation between the two cone-bottom elements, it is represented by "0". According to the determined dominance relation among the different cone-bottom elements, the weight distribution among the different cone-bottom elements is calculated by using the weight calculation principle of analytic hierarchy process, thus getting the matrix A. In the closing and renovating stage, the matrix A is a square matrix with 16 rows by 16 columns.

Step III If the cone -top elements e_{01} and e_{02} are regarded as a whole cone-top element e_0, the weight of e_0 at time t is $\omega_0^{(t)}$, and the weight of cone-bottom element is $(\omega_3^{(t)}, \ \omega_4^{(t)}, \cdots, \ \omega_{18}^{(t)})^T$. According to the weight decomposition principle of analytic hierarchy process:

$$\omega_0^{(t)} = \omega_3^{(t)} + \omega_4^{(t)} + \cdots + \omega_{18}^{(t)}, \quad \omega_{\mathrm{i}}^{(t)} = \beta_{\mathrm{i}} \times \omega_0^{(t)}, \ \mathrm{i}=3, 4, \ldots, 18 \tag{3}$$

Thus

$$W^{(t-1)}=B\times W^{(t-1)}\text{, t=1, 2, …} \tag{4}$$

$$B=\begin{pmatrix} \bar{\beta}_3 & \bar{\beta}_3 & \cdots & \bar{\beta}_3 \\ \bar{\beta}_4 & \bar{\beta}_4 & \cdots & \bar{\beta}_4 \\ \cdots & \cdots & \cdots & \cdots \\ \bar{\beta}_{18} & \bar{\beta}_{18} & \cdots & \bar{\beta}_{18} \end{pmatrix}_{18\times 18} \tag{5}$$

So matrix A and matrix B are obtained.

The components of $W^{(0)}$ are weighted non negatively and sum to 1. According to formula (4), assuming that the weight of the cone-bottom element is known at time (t-1), according to the compound weight principle of analytic hierarchy process:

$$\omega_i^{(t)}=\sum_{i=3}^{18}\omega_i^{(t-1)}\beta_{ij}\text{ , i≠j, and I, j=3,4, …, 18; t=1, 2, …} \tag{6}$$

$$\omega_i^{(t)}=\sum_{i=3}^{18}\omega_i^{(t-1)}\beta_{ij}\text{ , i≠j, and i, j=3,4, …, 18; t=1, 2, …} \tag{7}$$

Substitute it into a matrix to get:

$$W^{(t-1)}=A\times W^{(t-1)}\text{, t=1, 2, …} \tag{8}$$

Then

$$Q=AB\text{, t=1, 2, …} \tag{9}$$

The matrix Q is the weighted hypermatrix, and the $Q^{(+\infty)}$ limit matrix is obtained after matrix limiting, and then the weight of each cone-bottom element is obtained. The weight of the cone-top element is finally obtained by using the calculation method of formula (3). It should be noted that at this time, the sum of the element weights in the pointed cone element set is bound to be greater than 1, and the mixed weight of each element is obtained after normalization.

5.2 Analysis of Weight Calculation Results

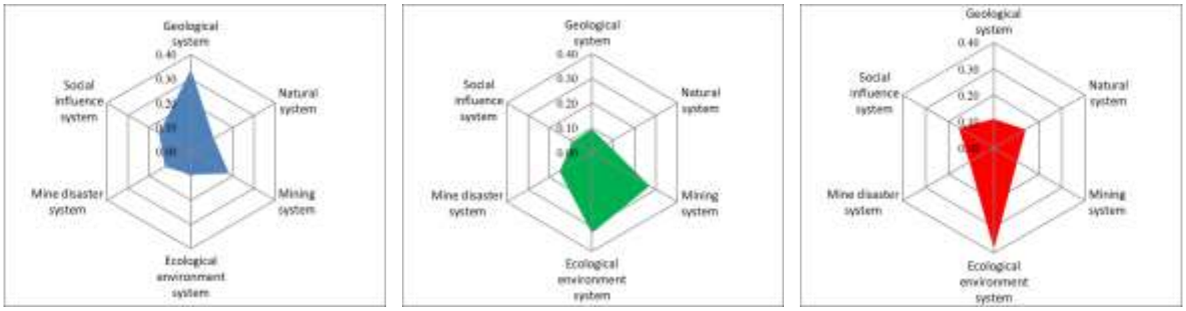
To weaken the subjective influence of industry experts on the importance scoring of the cone-bottom elements, various influencing factors are classified and graded according to the industry norms or standards and the research results of relevant scholars, and the expert scoring result is optimized. Based on the above pointed cone network model, the index weights of influencing factors of coal-water coordinated co-mining in 10 selected coal mines are evaluated. In order to avoid the specificity of calculation results of a certain coal mine, the weight results of coal mines in the same development stage are homogenized. The results of weight calculation for main influencing factors in the three stages of the full life cycle are shown in Table II, and the relative plot of weight distribution is shown in Fig. 7.

TABLE II. Weight distribution of influence factors in different stages

Criterion layer	Indicator layer	Planning and design stage		Construction and mining stage		Closing and renovating stage	
Geological system B1	Hydrogeological condition C1	0.3389	0.0483	0.0948	/	0.1096	0.0681
	Covering lithology and combination structure C2		0.0397		0.0269		/
	Aquifer property C3		0.1389		0.0260		/
	Aquifuge property C4		0.0610		0.0241		/
	Coal seam parameters C5		0.0509		/		/
	Types of environmental engineering geological models for water resources preservation during mining C6		/		0.0178		/
	Aquifer (aquifuge) restoration plan C7		/		/		0.0415
Natural system B2	Water resource carrying capacity C8	0.1086	0.0420	0.0704	0.0230	0.1402	0.0840
	Mine inflow C9		0.0666		0.0473		/
	Stored water in gob area C10		/		/		0.0562
Mining system B3	Designing scheme for water resources preservation during	0.1818	0.0958	0.2690	/	0.1034	/

Criterion layer	Indicator layer	Planning and design stage		Construction and mining stage		Closing and renovating stage	
	mining C11						
	Height of water flowing fractured zone C12		0.0860		/		0.0566
	Coal mining method and mining technology C13		/		0.1345		/
	Working face parameter C14		/		0.0700		/
	Recovery ratio C15		/		0.0645		/
	Size of gob area C16		/		/		0.0469
Ecological environment system B4	Soil erosion C17	0.0955	/	0.3259	0.0538	0.3850	0.0303
	Desertization C18		/		/		0.0392
	Vegetation coverage C19		/		0.0507		0.0317
	Coal gangue use ratio C20		0.0579		0.0616		0.0564
	Treatment rate of collapsed land C21		/		0.0610		0.0419
	Sewage and wastewater discharge C22		/		0.0500		/
	Utilization ratio and water quality of mine water C23		/		0.0487		/
	Water utilization rate and water quality in gob area C24		/		/		0.0376
	Utilization rate of abandoned wells and lanes C25		/		/		0.0943
	Decline of water table level C26		0.0376		/		0.0536
Mine disaster system B5	Geological disasters C27	0.1242	0.0539	0.1514	0.0619	0.1081	0.0519
	Mine water disasters C28		0.0703		0.0895		0.0563
Social influence system B6	Public support rate of the project C29	0.1511	0.0696	0.0885	/	0.1536	0.0831
	Overall labour productivity C30		/		0.0548		/
	Rate of return on costs		0.0815		0.0338		/

Criterion layer	**Indicator layer**	**Planning and design stage**	**Construction and mining stage**	**Closing and renovating stage**
	and expenses C31			
	Cost of ecological restoration C32	/	/	0.0705



a Planning and design stage b Construction and mining stage c Closing and renovating stage

Fig 7: Relative plot of weight results

Table 2 and Fig. 6 show that the geological system, mining system and social influence have higher weight in the planning and design stage. Parameters such as aquifer property, designing scheme for water resources preservation during mining and height of water flowing fractured zone are the key factors to judge the influence degree of disturbance in mining area. Therefore, based on the concept of source ecological detraction mining, detailed hydrogeological investigation should be carried out in the planning and design stage to improve the recognition accuracy of coal seam geological parameters, and the disturbance of coal mining on ecological environment can be controlled to be repairable by establishing a hydrogeological simulation model, selecting the technology of "water resources preservation during mining" suitable for the research area and accurately predicting the mine water inflow.

In the stage of construction and mining, ecological environment system, mining system and disaster system in mining area are the key factors to judge whether to realize the coordinated co-mining of coal-water resources. The indicators with higher weights are coal mining method and mining technology, mine water disasters, working face parameters, geological disasters, recovery rate and utilization rate of coal gangue, etc. Therefore, based on the failure mechanism of aquifer under mining conditions, reasonable mining parameters are adopted to maintain roof stability, reinforce coal pillars and replace strip coal pillars, maintain the stability of overlying strata, improve the utilization of coal gangue and realize the in-situ protection of aquifer. Applying the technology of comprehensive utilization and optimal allocation of mine water of "classification and quality +time-space coordination +intelligent allocation" will help the coal mine to reduce the risks of mine water disasters and geological disasters, and implement the ecological governance idea of "recovering while mining", so as to achieve the purpose of improving economic benefits and ecological benefits together.

In the closing and renovating stage, the ecological environment system, social influence system and natural system have great influence weight. As the ecological environment treatment is an important work at this stage, factors such as the utilization rate of abandoned wells and lanes, water resources carrying capacity, public support rate of the project, cost of ecological restoration, etc. should be considered as a whole, and ecological treatment targets should be formulated according to the needs of local production and life, so as to ensure that the restoration effect is consistent with the surrounding natural environment, while minimizing the impact of coal mine pit closure on social economy.

5.3 Discussion

In this study, 10 coal mines in different production stages in Mu Us Sandland are selected for investigation and analysis, and it is found that the coordinated co-mining of "coal-water" dual resources in underground mining is closely related to natural system, regional water resources status, ecological environment system, coal seam geology and coal mining technology (water resources preservation during mining, green mining), which is consistent with previous studies. In this paper, from the overall perspective of "Water- Coal-Socio-economy- Ecology", the indicator database of influencing factors of coal-water coordinated co-mining is preliminarily constructed, which reflects the comprehensive benefits of green development.

The coordinated development of coal resources and water resources is not a simple superposition of indicators among several systems, but a comprehensive consideration of the way and degree of mutual influence among various systems and indicators. How to quantify the evaluation results is one of the issues that academic circles attach importance to. In this paper, the "coal-water" coordinated development is taken as a whole, and a model is constructed by identifying the dependency and feedback relationship among the influencing factors in different life stages of coal mining, and by quoting the Cone-ANP, which can effectively weaken the arbitrariness of the subjective judgment of decision makers.

Some scholars have divided the life cycle of the coal industry from different perspectives. For example, Bian Zhengfu et al. divided the full life cycle of the coal industry into five stages: coal mining, processing, transportation, utilization and waste disposal. In this paper, considering the whole process of coal resources development, based on the internal relationship between aquifer destruction mechanism and groundwater resources under the influence of coal mining and the thinking of groundwater protection, coal-water co-mining is divided into three stages: planning and design, construction and mining and closing and renovating, which can basically cover the whole process of coal mining. The key technological innovation to realize high-quality development in the Yellow River Basin are to identify the main influencing factors of coal-water coordinated co-mining in coal mines mined by well workers at different life stages, and to realize disaster prevention and resource-efficient utilization of water resources mined in coal-series mining areas, especially in Mu Us Sandland with fragile ecological environment, and to establish a new "coal-water" coordinated co-mining model integrating mining and ecological protection.

VI. CONCLUSIONS

(1) Coal-water coordinated co-mining plays an important role in maintaining the ecological balance of western mining areas, alleviating the shortage of regional water resources, improving the utilization efficiency of water resources and promoting the development of local society. In this paper, based on the aquifer failure mechanism under the influence of mining, various influencing factors in the coal development process are divided into six systems: geology, nature, mining, ecological environment, mining disaster and social impact. According to the theory of source ecological detraction mining and full life cycle, the indicator database of influencing factors with real-time tracking and dynamic adjustment functions is constructed, which has certain reference significance for the research on the coordinated exploitation of coal and water resources in underground mining mines at the stages of planning and design, construction and mining and closing and renovating.

(2) Cone-ANP structure in different stages of the full life cycle of coal-water coordinated co-mining is constructed by using Cone-ANP analysis method, and the dependence and feedback relationships among different index elements are comprehensively analyzed, thus weakening the arbitrariness of decision makers' subjective judgment. With reference to industry norms, standards and research results of relevant scholars, the influencing factors are classified and graded, and the scoring results of experts are further optimized.

(3) According to the results of weight calculation, the factors that affect the coordinated co-mining of coal and water exist in all stages of its life cycle, and it is impossible to grasp the main influencing factors of the co-mining of coal and water from a single stage. Besides, geological structure of coal seam, mining method and technology, utilization rate and quality of mine water, vegetation coverage rate and so on are the key factors affecting the realization of

coal-water coordinated co-mining. Therefore, in the planning and design stage, the aquifer characteristics and coal seam structure in mining area should be identified and the appropriate "water resources preservation technology during mining" should be selected. In the construction and mining stage, the development height of water-conducting fissures, the quality of mine drainage water, the decline of underground water level and the vegetation coverage rate should be monitored, and the damage to the coal seam geological structure and ecological environment can be effectively reduced by adopting the technologies of reinforcing coal pillars, replacing strip coal pillars with filling bodies and utilizing drainage water efficiently. In the closing and renovating stage, attention should be paid to the follow-up work, such as efficient utilization of water in gob area and reuse of abandoned wells and lanes, to ensure the maximum ecological and social benefits of coordinated coal-water co-mining.

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REFERENCES

[1] Tan X L, Yan Q W, Wang J, et al. (2018) The dynamics of vegetation coverage and its influencing factors in Yushenfu coalmine. Chinese Journal of Ecology, 37(6): 16645-1653.
[2] Fan L M, Ma X D (2018) A review on investigation of water-preserved coal mining in western China. International Journal of Coal Science & Technology, 5(4): 411-416.
[3] Li W P, Wang Q Q, Liu S L, et al. (2018) Study on the creep permeability of mining-cracked N_2 laterite as the key aquifuge for preserving water resources in Northwestern China. International Journal of Coal Science & Technology, 5(3): 315-327.
[4] Xie H P, Wu L X, Zheng D Z (2019) Prediction on the energy consumption and coal demand of China in 2025. Journal of China Coal Society, 44(7): 1949-1960.
[5] Pan H Y, Geng Y, Tian X, et al. (2019) Emergy-based environmental accounting of one mining system. Environmental Science and Pollution Research, 26(14): 14598-14615.
[6] Zhang G X, Yuan X Z, Wang K H (2019) Biodiversity and temporal patterns of macrozoobenthos in a coal mining subsidence area in North China. Peer J, 7(2): e6456.
[7] Bai E H, Guo W B, Tan Y (2019) Negative externalities of high-intensity mining and disaster prevention technology in China. Bulletin of Engineering Geology and the Environment, 78(10): 5219-5235.
[8] Liu X M, Wang W J, Wang Z Y, et al. (2021) Evaluation of coal water coordinated green mining degree in ecologically fragile area based on GT-ANP theory. Coal Science and Technology, 49(8): 203-210.

[9] Xu J L (2020) Research and progress of coal mine green mining in 20 years. Coal Science and Technology, 48(9): 1-15.
[10] Wu Q, Shen J J, Wang Y (2017) Mining techniques and engineering application for "Coal-Water" dual-resources mine. Journal of China Coal Society, 42(1): 8-16.
[11] Fan L M, Ma X D, Jiang Z Q, et al. (2019) Review and thirty years prospect of research on water-preserved coal mining. Coal Science and Technology, 47(7): 1-30.
[12] Yuan L (2017) Scientific conception of precision coal mining. Journal of China Coal Society, 42(1): 1-7.
[13] Wang S M, Shen Y J, Sun Q, et al. (2020) Scientific issues of coal detraction mining geological assurance and their technology expectations in ecologically fragile mining areas of Western China. Journal of Mining and Strata Control Engineering, 2(4): 043531.
[14] Cao Z G, Zhang J M, Wang H, et al. (2021) Physical modelling and scenario simulation of coal & water comining in coal mining areas in western China. Journal of China Coal Society, 46(2): 638-651.
[15] Zhang J M, Li Q S, Cao Z G, et al. (2019) Quantitative analysis of green-mining and deep bionic-greenmining model. Journal of China Coal Society, 44 (11):3281-3294.
[16] Miao L T, Xia Y C, Duan Z H, et al. (2021) Coupling characteristics and intelligent integration technology of coal-overlying rock-groundwater-ecological environment in Yu-Shen-Fu mining area in the middle reaches of the Yellow River. Journal of China Coal Society, 46 (5): 1521-1531.
[17] Fan L M (2019) Some scientific issues in water-preserved coal mining. Journal of China Coal Society, 44(3): 667-674.
[18] Deng N D, Yang P, Lin P X, et al. (2017) Study on zone chart of engineering geological conditions of protected water resources during coal mining in Yushen Mining Area. Coal Science and Technology, 45(9): 167-174, 200.
[19] Hou P, Duan S L, Fan Y C, et al.(2021) Efficient utilization and intelligent allocation technology of mine water based on underground-surface and classification and quality. Safety in Coal Mines, 52(5): 96-103, 111.
[20] Zhang K, Gao J, Jiang B B, et al. (2019) Experimental study on the mechanism of water-rock interaction in the coal mine underground reservoir. Journal of China Coal Society, 44(12): 3760-3772.
[21] Hu Z Q, Xiao W, Zhao Y L (2020) Re-discussion on coal mine eco-environment concurrent mining and reclamation. Journal of China Coal Society, 45(1): 351-359.
[22] Li C H, Chen W F, Su H, et al. (2013) Cone-ANP: A new theoretical method of analytic network process based on the cone network. Journal of Management Sciences in China, 16(10): 11-24.
[23] Zhang J J, Jiang Y, Hu H L (2015) The General Structure and the Weight Calculation Method of Cone-ANP. Systems Engineering, 33(09):138-141.
[24] Saaty T L (2004) The Analytic Network Process: Decision Making with Dependence and Feedback. Pittsburgh: RWS Publications.