Energy Engineering

Tech Science Press

DOI: 10.32604/EE.2021.014203

ARTICLE

Evaluation of Environmental Quality for Abandoned Coal Mine Based on Environmental Vulnerability Index

Peng Qi[1,*] **and Yu Shang**[2,*]

[1]School of Law and Humanities, China University of Mining & Technology, Beijing, 100083, China

[2]School of Management, China University of Mining & Technology, Beijing, 100083, China

[*]Corresponding Authors: Peng Qi. Email: qp@cumtb.edu.cn; Yu Shang. Email: 108796@cumtb.edu.cn

Received: 10 September 2020 Accepted: 19 November 2020

ABSTRACT

With the increasingly prominent environmental problems of abandoned coal mines, this paper discussed the significance of environmental vulnerability assessment of abandoned coal mines. Environmental vulnerability assessment is essentially an assessment of environmental quality. At present, the research object of environmental impact assessment method and program of mine is mostly single factor. However, the impact of abandoned coal mine on the environment is multifaceted, which was summarized into nine prominent common problems. Based on these nine factors, the environmental vulnerability assessment model of abandoned coal mine based on multi-factor evaluation was established by using the analytic hierarchy process (AHP) method, the ranking criteria of nine factor indexes was proposed, the evaluation process was established, and the evaluation index system of environmental vulnerability of abandoned coal mines was established. The environmental vulnerability assessment method of abandoned coal mines has universal applicability, which can provide the basis for the government and enterprises to carry out treatment and planning of abandoned coal mine and promote the optimization of governance effect.

KEYWORDS

Abandoned coal mine; environmental vulnerability; analytic hierarchy process

1 Introduction

Coal is one of the most important fundamental material energy resources for the development of economy. Chinese coal industry grew gradually from thin foundation. Especially in thirty years since reform and opening up, it has been increased rapidly with the fast development of China economy and it plays a strong supportive role. Meanwhile, the foundation of coal industry which statuses in the national economic construction has increasingly highlighted.

The number of coal mines in China is huge and exceeds the sum of other country's coal mines. However, the amounts of abandoned coal mine are increasing due to some reasons, such as resource exhaustion after long-term exploration, political bankrupt, or being closed without license. The distribution of abandoned coal mines is in common with the production of coal mines in most provinces with different scale. It may hide a lot of risks and environmental problems which would endanger public safety and development of society.

Environmental vulnerability refers to the weak degree of environmental factors' resistance to interference and their own recovery ability. In essence, environment vulnerability evaluation is evaluated on environmental quality. Based on the investigation, the evaluation can rank the environmental quality with certain principle, criterion and suitable mathematical method, which can expose the main environmental problems of abandoned coal mine with "poor" or "very poor" index. The purpose of evaluation is to provide references for government supervision, and also for post-treatment of abandoned mines. So environmental quality evaluation is very important and necessary. Only after ranking how environmental quality and evaluating how serious the environmental problem are, can government and companies make reasonable planning. Meanwhile, the limited fund can be put into the mines with the most serious environmental problems in order to achieve the best optimized effect.

EVI (environmental vulnerability index) evaluation is raised after the vulnerability index method for mine water-bursting prevention. It is used in environmental quality evaluation to provide a series of approaches. At present, the research object is regarded as an isolated individual in the mine environmental impact assessment methods and procedures in China. In terms of evaluation content and evaluation elements, single factor assessment such as environmental pollution, geological disasters, water and soil loss and noise pollution is paid more attention, and the environmental problems caused by multiple factors are less evaluated [1–6].

The impact of abandoned coal mines on the environment is multifaceted. Based on the investigation and analysis, the impact of abandoned coal mines on the environment is summarized into nine prominent common problems. The nine factors are taken as contributors in EVI evaluation method. With certain mathematical method, they are combined to identify the vulnerable degree in abandoned coal mine [5]. EVI evaluation method of abandoned coal mines has universal applicability and any abandoned coal mine environmental problems can be applied in the model.

1. Single factor evaluation. Single factor evaluation standard will be generated by analyzing each factor impact in environmental vulnerability.
2. Comprehensive evaluation. On the basis of analysis for single factor, the evaluation model could be built by evaluating the environmental vulnerability according to index weight with mathematical method.

2 Process of Environmental Vulnerability Evaluation

This manuscript uses comprehensive evaluation method. To evaluate environmental quality of a coal mine, the multi-factor evaluation model must be built at first. Then, with some mathematics method, the index weight of each factor should be quantified and the value function should be defined. Finally, evaluation index will be confirmed by dividing evaluation value intervals. The specific work flow chart is as follows (Fig. 1) [7–10].

3 Environmental Vulnerability Evaluation Model

The environmental vulnerability index method introduces primary model of EVI (Formula 1). According to the value range of vulnerability index, the amount of ranks is obtained. Finally, the ranks of environmental vulnerability are calculated based on grades of evaluation.

$$EVI = \sum_{i=1}^{n} W_i \cdot \mathrm{f_i}(\mathrm{x}, \mathrm{y}) \tag{1}$$

EVI is environmental vulnerability index; W_i is weight of the i factor, and $\sum_{\mathrm{i}=1}^{n} W_i = 1$; $\mathrm{f_i}(\mathrm{x}, \mathrm{y})$ is geographic coordinates; n is the number of factors.

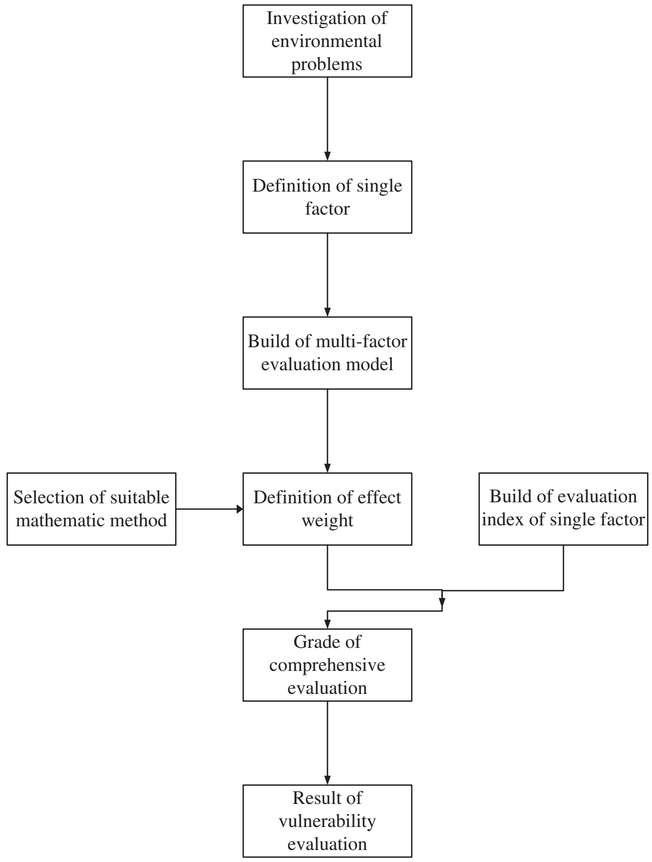

Figure 1: Comprehensive evaluation process of abandoned coal mine

The factors which affect the environmental vulnerability are complicated. They are varied to some degree in different region and varied according to how the environment is spoiled and how serious it is. So it is necessary to use proper mathematical approach to define the contribution rate of each factor to EVI.

4 Contribution Value of EVI on a Certain Abandoned Coal Mine

4.1 Definition of Weight by AHP

The Analytic Hierarchy Process (AHP) is a qualitative and quantitative combination of multiple criteria decision theory. It is a simple, flexible and practical multi-criteria decision method, which was put forward by American operation research professor T. L. Saaty in the 1970s. It is also one of effective ways to transform semi-qualitative and semi-quantitative questions into quantitative problems.

The AHP method can reflect the thought of system analysis and system synthesis more thoroughly. It can use little quantitative information to make the decision mathematically, and then provide convenient decision way for multi-criteria, multi-objective or non-structural properties of complex decision problems, which is based on the exploration of the essence, influencing factor and internal relations of the complex problem. This method is particularly suitable to solve the problem that the decision result is difficult to be directly and accurately obtained. The AHP method divides complex problems into objects, criterion, scheme (factor) and other number of levels. Elements in each level of the layer will be compared according to certain criterion, which constitutes the judgment matrix. By calculating the largest eigenvalue and its corresponding orthogonal eigenvectors of the judgment matrix, the factor weight would be obtained. On this basis, the proportion of the factor in each layer could come out. At last, the solution (weight) will be obtained [11,12].

4.2 Establish a Hierarchical Analysis Model of In Abandoned Coal Mines

According to the analysis of nine factors affecting the environmental quality of abandoned coal mines, the research objects were divided into three levels. Environmental vulnerability assessment of abandoned coal mines is the ultimate aim of the problem and should be used as the target layer (level A) of the model. The environmental vulnerability of abandoned mines is determined by the problem of "three wastes," geological disasters, ecological and resources destruction in coal mines, but the influence mode must be reflected by relevant factors. This is the intermediate link of solving the problem. Namely, the criterion layer (level B) of the model. Solid wastes such as coal gangue, mine waste-water, mine exhaust, ground subsidence and cracks, slope failure, land resource destruction, soil and water loss and pollution, landscape destruction, water environment and water resources destruction, etc. The nine factors constitute the decision layer (level C) of this model, and through decision making on this level, the required solution can be finally achieved, and the environmental vulnerability of abandoned coal mines can be classified [4] (Fig. 2).

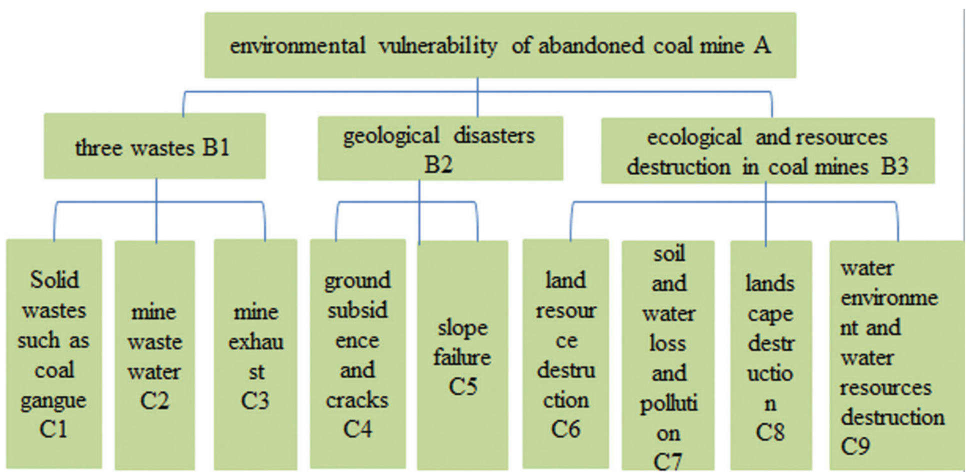

Figure 2: Hierarchical model of environmental vulnerability assessment of abandoned coal mine

4.3 Structured Judgment Matrix

Comparing the influence of n factors $X = \{x_1, x_2, x_3, \ldots, x_n\}$ on a particular factor Z. Take two factors x_i and x_j at a time, the ratio a_{ij} represents the impact of x_i and x_j on Z, and the results of the comparison $A = (a_{ij})_{n\times n}$ are expressed in a matrix, corresponding to the feature vector w of the maximum feature value of λ max [13–15].

$$A = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \cdots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & \cdots & w_3/w_n \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \cdots & w_n/w_n \end{bmatrix}$$

4.4 Weight Calculation

For different individual abandoned coal mines, after establishing an environmental vulnerability assessment hierarchy model, a judgment matrix is established according to the actual environmental conditions of the target mine. The contribution value of various factors to the vulnerability of mine environment is obtained by calculation and analysis [5]. The paper adopts the following indicators as the basis for environmental quality evaluation of abandoned coal mines based on national or industrial standards and combined with the actual conditions of abandoned coal mines.

4.4.1 Rank Criteria of Solid Waste Like Coal Gangue Index

For setting rank criteria of solid waste in abandoned coal mines, the paper mainly considers the land pressure effect of solid waste, the spontaneous combustion effect of coal gangue, the radon stability of solid waste accumulation area, dust lifting and filtration pollution [6]. According to the relevant national standards, the environmental rank criteria of solid waste like coal gangue index shall be formulated (Tab. 1).

Table 1: Rank criteria of solid waste like coal index

Evaluation index rank (fractional value)	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Land area (km^2) and type	<0.1 uncultivated land	0.1–0.5 Mainly sparse grass, shrubs and woodlands.	0.5–1 Grassland, woodlands and industrial and mining sites	>1 Agricultural land
Spontaneous combustion of coal gangue	Not spontaneous combustion	Small range of occasional spontaneous combustion.	Local spontaneous combustion	Most normal spontaneous combustion
Slope stability of solid waste accumulation	$F_S < F_{st}$	$1.05 < F_S < F_{st}$	$1.00 < F_S < 1.05$	<1.00
Dust trap (mg/m^3)	<60	60–80	80–100	>100
Leachate, etc.	$p_{\text{integrated circuit}} \leq 1.0$	$1.0 < p_{\text{integrated circuit}} \leq 2.0$	$2.0 < p_{\text{integrated circuit}} \leq 3.0$	$3.0 < p_{\text{integrated circuit}}$

[1]FS is a slope stability coefficient, and FST slope stability allows safety coefficient.
[2]Implementation of the comprehensive emission standards for atmospheric pollutants.
[3]Implementation of soil environmental quality standard for the leachate land leaching pollution GB 15618-1995.

4.4.2 Rank Criteria of Mining Wastewater Index

The rule making of environmental rank criteria of mining wastewater index is mainly from two aspects: underground wastewater and surface wastewater. The rank of underground wastewater evaluation index mainly considers the pollution of various metal objects and chemical elements in waste water. The rank of surface wastewater evaluation index mainly takes into account factors such as the discharge water quality index and the area of stagnant water by mining subsidence or extracting well water and waste water for coal dressing.

The one-way factor standard in the scale of mine wastewater index (Tab. 2) implements the Surface Water Environmental Quality Standard (GB3838-2002) and Quality standard for ground water (GB/T14848-93). The main indexes include water temperature, pH value, dissolved oxygen, chemical oxygen demand (COD), five-day BOD (BOD5) and ammonia nitrogen (NH3-N), total phosphorus (P), total nitrogen (N) (including major metallic elements and harmful elements).

4.4.3 Rank Criteria of Mine Waste Air Index

The unidirectional factor index in mine waste air emission index grade standard (Tab. 3) is mainly implemented by reference to the comprehensive emission standard for atmospheric pollutants (16297-1996). Each factor index value is approved and evaluated according to this standard.

Table 2: Rank criteria of mining wastewater index

Evaluation index rank	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Surface stagnant water area (km^2)	<0.05	0.05–0.3	0.3–0.55	0.55–0.8
Pollution levels	Pollution free (level I)	Mild pollution (level II)	Moderate pollution (level III)	Heavy pollution (level III)
Single factor	Not exceeding the standard	Exceeds less than 1 times	Exceeding 1–5 times	More than 5 times

Note: The quality evaluation of surface water carries out the *Environmental Quality Standard of Surface Water* GB3838-2002. The quality evaluation of ground water carries out the *Quality standard for ground water* GB/T14848-93.

Table 3: Rank criteria of mine waste air index

Evaluation of index level	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Pollution level	Pollution free (level I)	Mild pollution (level II)	Moderate pollution (level III)	Heavy pollution (level IV)
Single factor	Not exceeding the standard	Exceeds less than 1 times	Exceeding 1–5 times	More than 5 times

Note: Evaluation of mining waste air quality implements the *Comprehensive Emission Standards for Atmospheric Pollutants* GB16297-1996.

4.4.4 Rank Criteria of Geological Hazard Index for Ground Surface Subsidence, Crack and Slope Instability

The environmental grade standard of abandoned coal mine geological hazard index is mainly based on rank criteria of geological hazard and damage degree index (Tab. 4).

Table 4: Rank criteria of geological hazard and damage degree index

Degree	Grade of hazard and damage	Number of Death toll	Number of persons at risk	Direct economic loss (ten thousand yuan)
Level I (0.3)	General (light)	<3	<10	<100
level II (0.5)	Large (medium)	3–10	10–100	100–500
level III (0.7)	Heavy (heavy)	10–30	100–1000	500–1000
level IV (0.9)	Special heavy (special heavy)	>30	>1000	>1000

Note: [1]Damage classification refers to the classification of the degree of geological disaster that has occurred. "The number of deaths" or "direct economic losses" shall be assessed according to the classification of the disasters. The classification name adopts the general, large, heavy and special heavy.
[2]Hazard degree classification means the prediction and classification of the hazard degree of possible geological disasters. The "number of people at risk" or the pre-evaluation of "direct economic loss" are used for evaluation. The classification name adopts light, medium, heavy and special heavy.

The rank criteria of ground surface subsidence and ground crack index are as follows (Tab. 5).

Table 5: Rank criteria of geological hazard scale index (Ground surface subsidence, Ground crack)

Grade of damage	Small	Medium	Large	Special large
Evaluation level	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Ground surface subsidence/Impact range (km^2)	<1	1–10	10–100	>100
Ground crack/Impact range (km^2)	<10	10–100	100–1000	>1000
Collapse/Volume (10^4 m^3)	<1	1–5	5–50	>50
Landslide/Volume (10^4 m^3)	<2	2–20	20–200	>200
Mudflow/Volume (10^4 m^3)	<1	1–10	10–20	>20
Mudflow/Watershed area (km^2)	<1	1–5	5–10	>10

Note: The classification of disaster grade is carried out according to the work standard of the China Geological Survey, Regional Geological Survey (trial) (DD2004-02).

4.4.5 Rank Criteria of Land Resource Damage Degree Index

The rank criteria of land resource damage degree index of abandoned coal mine mainly includes damaged land, land desertification index (Tab. 6) and occupied and damaged land index (Tab. 7).

Table 6: Rank criteria of land desertification degree index (Desertification)

Rank	Potential desertification	Mild desertification	Moderate desertification	Severe desertification
Degree of index	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Degree of desertification	Sandstorm is weak, Naked sand is less than 10%, and most of the area of sand is less than 1 m.	Sandstorm is obvious. Naked sand takes 10–30%, the thickness is less than 1 m.	Sandstorm is frequent. Naked sand is 30–50, and the thickness is a few meters.	Sandstorm is strong. Naked sand takes over 50%, and the thickness is from 10 to 40 m.
Vegetation cover	Vegetation cover is greater than 40%.	Vegetation cover takes 20–40%.	The vegetation cover is less than 20%.	The vegetation cover takes less than 10%.

Table 7: Rank criteria of occupied and destroyed land by coal waste index

Evaluation index grade (fractional value)	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Occupied and damaged land area: waste-rock yard, venue for working (km^2)	<0.1	0.1–0.5	0.5–1	>1
Destruction of land types	Wasteland	Sparse grass, bushes	Grassland, woodlands, industrial and mining construction sites	Agricultural land
Direct economic loss (ten thousand yuan)	<100	100–500	500–1000	>1000

4.4.6 Rank Criteria of Soil and Water Loss and Soil Pollution Index

The standards for classification of soil erosion and pollution indexes in abandoned coal mines (Tab. 8) are mainly drawn up from four aspects: Soil erosion, soil pollution levels, comprehensive soil pollution index and pollution level. The specific individual indicators are carried out with reference to the soil environmental quality standard (GB 15618-1995).

Table 8: Rank criteria of soil and water loss and soil pollution index

Evaluation index grade (fractional value)	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Soil erosion	Basically no soil erosion	Slight soil erosion	Local soil erosion	Extensive soil erosion
Soil pollution levels	warning line (level I)	Mild pollution (level II)	Moderate pollution (level III)	Heavy pollution (level IV)
Soil integrated pollution index	$P_{\text{integrated circuit}} \leq 1.0$	$1.0 < P_{\text{integrated circuit}} < 2.0$	$2.0 < P_{\text{integrated circuit}} \leq 3.0$	$3.0 < P_{\text{integrated circuit}}$
Pollution levels	Semi-clean	The soil pollutant exceeds the background value, as minor pollution, and the crops begin to be polluted.	The soil crops are severely polluted.	The soil crops are seriously polluted.

Note: Soil pollution implements *Soil Environmental Quality Standard* GB 15618-1995.

4.4.7 Rank Criteria of Failure of Landscape Index

The rank criteria of failure of landscape index based on the actual environment of the abandoned coal mine, and Tab. 9 is formulated.

Table 9: Rank criteria of failure of landscape index

Evaluation index grade (fractional value)	Better (0.3)	Good (0.5)	Bad (0.7)	Worse (0.9)
Landscape stability[1]	More stable	Much stable	General	Much unstable
Landscape productivity indicators[2]	Higher	High	General	Worse
Heterogeneity index of landscape[3]	Higher	High	General	Worse

Note: [1]Landscape stability refers to the ability of landscape resistance to external interference. Landscape changes need to be within the limit of stability in order to move the landscape to a higher level of stability, whether natural or human interference, once beyond the ability of the landscape self-restoration. Landscape ecosystem inevitably tends to deteriorate, directly affecting human survival and development.
[2]The level of landscape productivity is the input-output level of a landscape ecosystem.
[3]The landscape is a heterogeneous land area, composed of an interactive ecosystem with similar forms and repeated occurrence, with a certain spatial structure. The higher the heterogeneity of the landscape, the stronger the function of the landscape, and the stronger the ability of recover after the destruction of the landscape ecosystem.

4.4.8 Rank Criteria of Water Resource and Water Environment Impact and Damage Index

Rank criteria of water resource and water environment impact and damage index (Tab. 10) mainly considers the influence of coal mining on aquifer water quantity, water ecology, people's production and living, industrial and agricultural production and other factors on water resources and water environment.

Table 10: Rank criteria of water resource and water environment impact and damage index

Impact degree (fractional value)	Mild effect (0.3)	Moderate effect (0.5)	Severe effects (0.7)	Extreme influence (0.9)
water resource and water environment impact and damage.	The quantity of water resources does not change much or the water environment does not affect much.	Partial impact on agriculture in mining areas and drinking water.	The water level of most wells and springs has dropped, and the population and agricultural production have been greatly affected with some impact on the ecological environment.	Most of wells and springs are dry, and residents' difficulty have drinking water or lead to the deterioration of the ecological environment.

5 Classification of Environmental Vulnerability Index

Take a certain abandoned coal mine as example. After the weight of each factor has been quantified, the influence value should be obtained. China Geological Survey issued the standard of China geological survey "Principle of Survey in Regional Environmental Geology (try out) (DD2004-02)" in October, 2004. With the degree of regional environmental geology, the evaluation region can be divided by the index value of geological environmental quality. The classification is good, better, worse and bad. By analogy with this principle, the index factor of environmental vulnerability in abandoned coal mine can be classified as I, II, III and IV.

The standard score of each assignment: I = 0.3, II = 0.5, III = 0.7 and IV = 0.9. The standard of assignment of each factor and the comprehensive evaluation are defined by weighted score (Tab. 11).

Table 11: Value-determined standard rank and weighted score corresponding standard of different factors

	I	II	III	IV
Score of each index factor	0.3	0.5	0.7	0.9
Weighted score of each index factor F0	<0.4	0.4–0.6	0.6–0.8	>0.8

After the weight of each factor is obtained and quantified, the environmental vulnerability should be classified. Quantitative value is between 0.3 and 0.9 with $W_i \in [0, 1]$ and $\sum_{i=1}^{9} W_i = 1$. The index of EVI is between 0.3 and 0.9 according to the formula of environmental vulnerability in abandoned coal mine, Formula 2.

$$EVI = \sum_{i=1}^{9} W_i \cdot f_i(x, y) \quad (2)$$

In this paper, the degree of environmental vulnerability evaluation can be classified as weak, relatively weak, moderately weak and strong weak. They are as follows (Fig. 3):

Weak $EVI \in [0.3, 0.45)$

Relatively weak $EVI \in [0.45, 0.6)$

Moderately weak $EVI \in [0.6, 0.75)$

Strong weak $EVI \in (0.75, 0.9]$

Once the environmental vulnerability method is chosen to evaluate the vulnerable degree of abandoned coal mine, the EVI can be used according to the above classification.

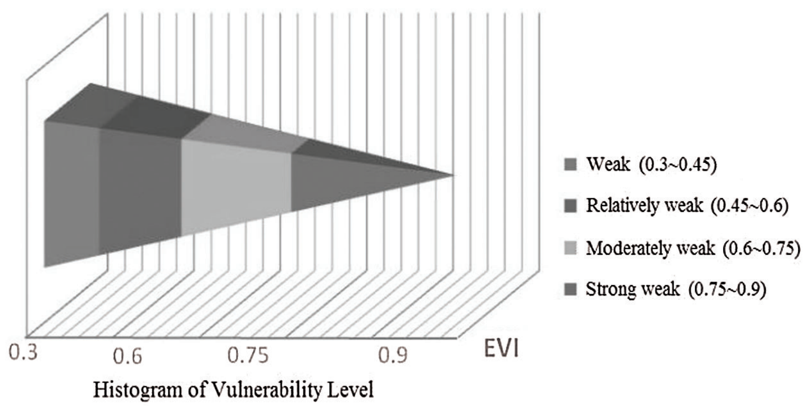

Figure 3: EVI hierarchical of abandoned coal mine

6 Conclusions

The method of environmental vulnerability evaluation is a new type of evaluation on multi-factor. When dealing with the problems of abandoned coal mine, it has the following advantages and characteristics.

First, according to the complexity and diversity of the influencing factors, it overall considers the influence and overcomes the one-sidedness of single factor, which combines the universality and particularity of environmental problems and achieves harmony and unification.

Second, the integrity and system of environmental vulnerability index method is strong. Through the discussion of EVI model, it is obviously that both of the application of mathematic theory and the definition of quantitative value are indispensable with strong system.

At last, the EVI evaluation method is universal in abandoned coal mine. This method comprehensively considers several problems of abandoned coal mine. Each problem is regarded as a factor, which can make the environmental problems applied in the model by the contribution of weight.

In a word, with the resources of some coal mines exhausted and small-scale coal mines shut down or integrated, the environmental evaluation is of great necessity and significance. It is required to strengthen the research of environmental evaluation method in abandoned coal mine, which are the important premise and the only way to achieve the scientific treatment on environmental problems with broad development space and bright future.

Funding Statement: Research Funds for Yue Qi Young Scholars (No. 2018QN11); the Fundamental Research Funds for the Central Universities (2009QG09).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Qiao, A. P. (2019). Discussion on soil environment impact assessment method in environmental assessment of coal mine projects. *Shanxi Chemistry Industry, 3,* 220–222.
2. Chen., F. (2020). Impact from coal winning on spring area environment. *Coal Geology of China, 32(4),* 34–37.
3. Li, P. (2019). Environmental impact assessment of closed pit mine. *Coal and Chemical Industry, 42(11),* 115–118.
4. Yan, C. D., Dai, H. J., Guo, W. (2017). Evaluation of ecological environmental quality in a coal mining area by modelling approach. *Sustainability, 9(8),* 1265. DOI 10.3390/su9081265.
5. Wu, Q., Zhang, Z. L., Zhang, S. Y., Ma, J. F. (2007). New practical methodology of the coal floor water bursting evaluating II: the vulnerable index method. *Coal Industry, 32(11),* 1121–1126.
6. Sun, X., Wang, F. W., Guo, T. F., Wang, H. Q., Guo, Z. G. et al. (2019). Occurrence and risk assessment of polycyclic aromatic hydrocarbons in topsoil of an abandoned coal mine area in Chongqing. *Earth and Environment, 47(4),* 502–509.
7. Zajdlik, B. A. (2016). A statistical evaluation of the safety factor and species sensitivity distribution approaches to deriving environmental quality guidelines. *Integrated Environmental Assessment and Management, 12(1),* 380–387.
8. Rahman, M. R., Shi, Z. H., Chongfa, C. (2014). Assessing regional environmental quality by integrated use of remote sensing, GIS, and spatial multi-criteria evaluation for prioritization of environmental restoration. *Environmental Monitoring and Assessment, 186(11),* 6993–7009. DOI 10.1007/s10661-014-3905-4.
9. Lars, J. H. (2015). Evaluation of the economic and environmental feasibility of heat pump systems in residential buildings, with varying qualities of the building envelope. *Renewable Energy, 76,* 699–705.
10. Lee, I. Y., Hwang, H. D., Lee, J. G., Yu, N. Y., Yun, J. H. et al. (2017). Modeling approach to evaluation of environmental impacts on river water quality: A case study with Galing River. *Ecological Modeling, 353,* 167–173. DOI 10.1016/j.ecolmodel.2017.01.021.
11. Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15(3),* 234–281. DOI 10.1016/0022-2496(77)90033-5.
12. Wang, W., Su, J. Y., Ma, D. H., Tian, J. (2012). Evaluation of rock mass quality based on fractal interpolation model. *Central South University (Science and Technology), 43(12),* 4827–4833.
13. Brown, T., Du, S. K., Eruslu, H., Sayas, F. J. (2018). Analysis of models for viscoelastic wave propagation. *Applied Mathematics and Nonlinear Sciences, 3(1),* 55–96. DOI 10.21042/AMNS.2018.1.00006.
14. Carlos, F. P. (2018). Perfect phase-coded pulse trains generated by Talbot effect. *Applied Mathematics and Nonlinear Sciences, 3(1),* 23–32.
15. Khellat, F., Beyk, M. (2018). A global solution for a reaction-diffusion equation on bounded domains. *Applied Mathematics and Nonlinear Sciences, 3(1),* 15–22. DOI 10.21042/AMNS.2018.1.00002.