

Research Article

Dynamic Evaluation of Water Utilization Efficiency in Large Coal Mining Area Based on Life Cycle Sustainability Assessment Theory

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Coal mining enterprises have a variety of water sources, complex drainage structures, long production chain, and many links, which lead to uncoordinated water utilization and low water efficiency. Taking a large coal mining area of China as an example, a dynamic model was established to evaluate the water utilization efficiency based on the Life Cycle Sustainability Assessment (LCSA) theory. In the model, the influence of five aspects (including resources, economy, technology, society, and environment) and 19 factors was considered. The game theory method was adopted to calculate the fusion weights of the 19 factors according to the analytic hierarchy process and CRITIC method. The CW-VIKOR method was used to explain the dynamic evaluation results of water efficiency in the coal mining area. The results show that the environmental impacts of the mining system mainly come from three aspects: regional drainage, domestic sludge landfill and disposal, and water system electricity consumption. Electricity consumption in water systems has the greatest environmental impact, accounting for about 73%, regional drainage for about 26%, and domestic sludge landfill and disposal for about 1%. The CW-VIKOR approach can harmonize the interrelationships among resources, economy, technology, society, and environment. It is an effective method for LCSA of water resource in the coal mining area. The reliability of the evaluation results is high and close to the actual situation. The dynamic model established in this paper is also applicable to other coal mine areas, and only the factor weights need to be modified according to the specific characteristics of each coal mine. The model can provide guidance for optimal exploitation and allocation of coal mine water resources.

1. Introduction

China is both a major producer and consumer of coal. Coal is the main energy supply that underpins China's rapid economic growth. With the shortage of water resources and the increasing cost of water, as well as more and more stringent standards for wastewater discharge, it is imperative to improve the water recycling efficiency of coal enterprises. Coal enterprises have diversified water use sources, including surface water, groundwater, and reuse water. Meanwhile, its water use structure is complex, and different water use units have different requirements for water quality [1]. The reused water can only meet the low water quality requirements of coal mine production, coal preparation plant, and pit water

sprinkling [2]. It results in a low reuse rate of reused water. In the mining activities of coal industry, water resources have the life cycle of water intake, water distribution, utilization, drainage, water treatment, and recycling/waste [3]. The multiple attributes of water resources determine that it has important influence on economy, environment, and energy in each stage of life cycle. It is of great practical significance for the rational development, optimal allocation, and sustainable utilization of coal mine water resources to carry out the comprehensive evaluation of the life cycle use and management of water resources in coal mine areas [4].

At present, the research on water resource sustainability mainly includes the research on the quantity and the quality of water resources [5, 6], water resource security [7, 8], water

resource carrying capacity [9–11], water resource vulnerability [12, 13], and water resource utilization efficiency [14, 15].

The research on water resource utilization efficiency during coal mining can be summarized into two aspects. First, it focuses on the mine water quality treatment technology and the treatment rate improvement. For example, Zhou et al. [16] integrated two water treatment processes of pressurized air-water mutual flushing filter and aerated oxidation tank. They reused mine water in situ after using goaf to treat mine water, which achieved good results. Gu et al. [17] put forward the concept of channel-reservoir-use to protect and utilize the coal mine groundwater. Mao et al. [18] studied and applied zero discharge treatment technology according to the characteristics of mine water with high salinity in large coal bases in western China. He et al. [19] summarized the mature mode and new technology of mine water comprehensive utilization system. Second, some researchers studied the consumption and pollution of water resources in the process of coal mining. For example, Ding et al. [20] applied the whole life cycle theory to establish an evaluation model for the water footprint of energy production.

Lifecycle concept is a scientific approach to managing resource consumption and pollution. The nature life cycle of water resources refers to the whole life cycle of precipitation, runoff, confluence, and evaporation. Based on the natural and social attributes of water resources, Lundin et al. [21] divided the life cycle of water resources into four types: cycle, development, utilization, and recovery life cycle. Wang et al. [22] made a preliminary discussion on the theory of water resource life cycle from aspects of connotation, characteristics, flow of material quantity and value quantity of water resource life cycle, etc. Zhao et al. [23] analyzed the relationship between human system and water resource system in the life cycle of water resources utilization. They proposed the integrated management model of water resources life cycle based on the theory of harmonious between human and water. Based on the provincial energy input-output table in China, Zhang et al. [24] calculated the life-cycle water intake, water consumption, and wastewater discharge indexes of 8 types of energy varieties in China and calculated their environmental impacts using the Pfister method. Based on the life cycle assessment theory, Tong et al. [25] used the GaBi database to compare and quantify the impacts of industrial sewage reuse on the environment under different scenarios.

In terms of life cycle assessment research of the water supply system, Godsken Berit [26] established the ASTA decision support system including environmental, economic, and social sustainability based on the ranking distribution weight and analytic hierarchy process of the multicriteria decision analysis method. The sustainability of water supply technology was evaluated by life cycle assessment, impact assessment of fresh water extraction, and multicriteria decision analysis. Studies have identified three phases that contribute significantly to the global environmental load: drainage, wastewater treatment, and construction of sewerage systems. Bhakar et al. [27] studied the potential environmental impacts of using groundwater as the source of irrigation and carried out a life cycle assess-

ment of groundwater supply systems in severely arid areas of India to achieve sustainable groundwater management. The evaluation results show that the use of copper in the water supply system and the energy consumption during the mining process have a significant impact on the environment. Xue et al. [28] assessed the life-cycle environmental and economic impacts of urban water supply and wastewater systems in Greater Cincinnati. They illustrated the overall distribution of energy, resources, and costs in a typical urban centralized water supply system. Hadjikakou et al. [29] integrated multiregional input-output life cycle assessment, social impact analysis, and multiobjective decision analysis to establish a framework for sustainability assessment of water supply schemes. Garcia et al. [30] used the life cycle assessment method to assess the environmental and social impacts of Mexico's urban water supply system. They identified the stages and processes that have important impacts on the environment and society and analyze the significance of sustainable water supply system development.

Above all, there are still several aspects of water resource utilization in coal mine production that need further study: (1) lack of comprehensive evaluation model of water resource consumption for whole coal mining process; (2) lack of research on the comprehensive impact of water resource utilization in coal mine production on resources, economy, technology, society, and environment; and (3) lack of effective analysis methods of sensitive indexes affecting the water resource system for the whole coal mining process.

The establishment of the water resource life cycle evaluation system for the typical coal mining area and the identification of important indexes affecting the water circulation system of coal mines can provide scientific support for the improvement and optimization of the coal industry water use system [31, 32]. In this paper, taking a large coal mining area of China as an example, a dynamic model was established to evaluate the water utilization efficiency based on the Life Cycle Sustainability Assessment (LCSA) theory. In the model, the influence of five aspects (including resources, economy, technology, society, and environment) and 19 factors is considered. The game theory method was adopted to calculate the fusion weights of the 19 factors according to the analytic hierarchy process and CRITIC method. The CW-VIKOR method was used to explain the dynamic evaluation results of water efficiency in the coal mining area.

2. Overview of the Study Area

China Coal Pingshuo Group Co., Ltd. is a super large coal production enterprise. Its reserves are 6.14 billion tons. In this paper, the research area is part of the Pingshuo coal mine. It mainly contains two surface mines (Antaibao and Anjialing) and two underground mines (Jinggong No.1 and Jinggong No.2) (Figure 1), with production capacity of 22 million t/a, 20 million t/a, 10 million t/a, and 10 million t/a, respectively. The four coal mine areas are selected as the research area to evaluate the sustainability of water resources during whole coal production process.

In the research area, the water sources for production and daily life include surface water, groundwater, reservoir

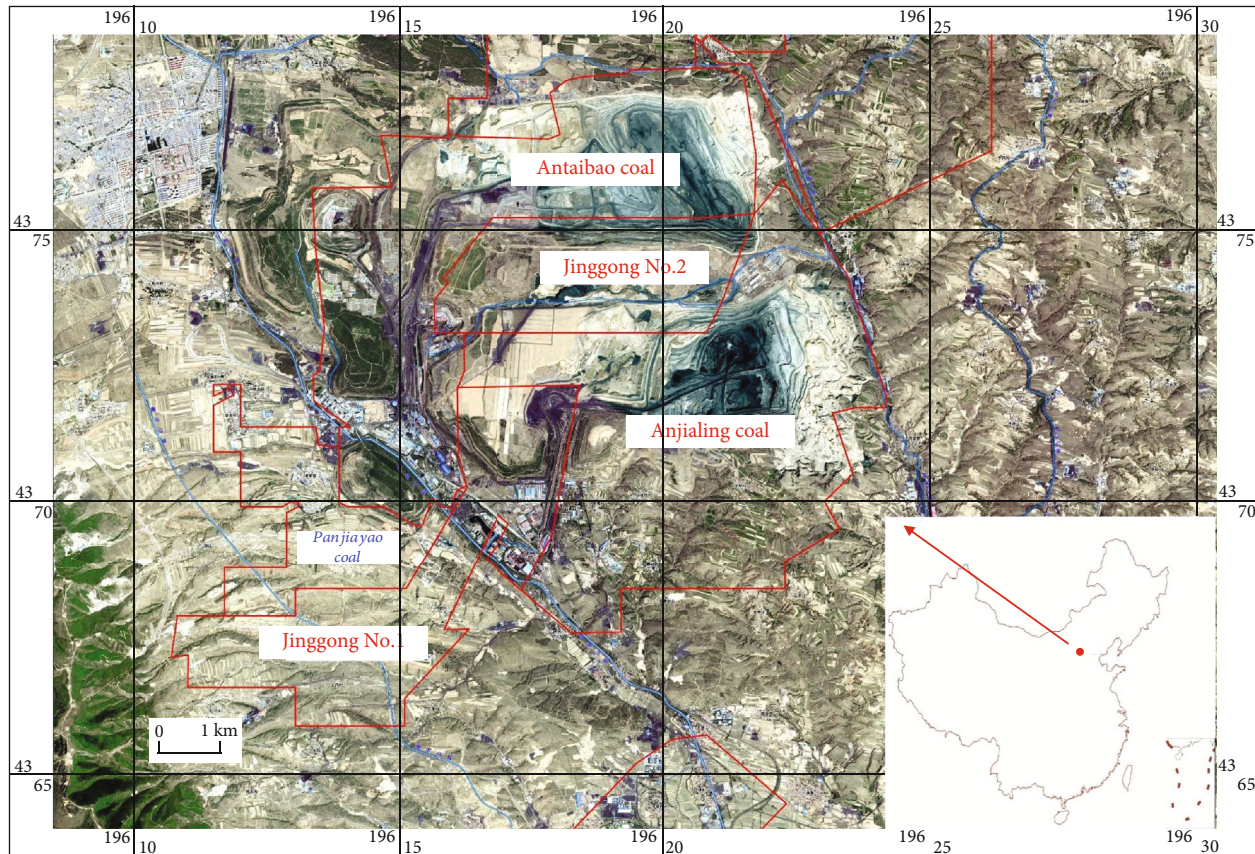


FIGURE 1: Location of the research area.

water, and reclaimed water. The surface water is supplied by the Yellow River with an annual water supply capacity of 5 million m^3 . The groundwater is from the Liujiakou water source region with an annual water supply capacity of 4.015 million m^3 . Regional sewage discharge points are scattered and cannot be collected in the form of gravity flow. The surface mines require large amount of water. Underground mining production needs less water, and the drainage points are more concentrated.

The research area has diversified water sources, complex drainage structure, long chain and many links, and complex changeable characterization indexes. Therefore, there exists water imbalance among different regions of the coal enterprise, which requires adjustment and optimization through scientific evaluation.

3. Methodology

Based on the LCSA theory, we established a life cycle evaluation model of coal mine water resources. The multiobjective decision analysis method was used to explain the evaluation results of the model. The sustainability of the life cycle of water resources in the mine area was analyzed. The methodology flow chart is shown in Figure 2.

3.1. Objectives and Scope. The research object of this paper mainly focuses on the whole circulation system of water

resource life cycle in the research area. The data are obtained from 2015 to 2018.

In the sustainability assessment of the life cycle, the functional unit includes the annual operation status of water system from five dimensions, namely, resource consumption, economic benefit, technical performance, social impact, and environmental impact. The evaluation period of the functional unit is 1 year, and all inputs and outputs are based on this functional unit. System boundary includes physical boundary, geospatial boundary, and time series. The physical boundary is the six stages of water intake, water distribution, utilization, drainage, water treatment, and reuse/waste in the life cycle of water resources. The spatial boundary is the geographical boundary of the study area. The time boundary is from 2015 to 2018.

3.2. LCSA Lists

3.2.1. Environmental Impact List

(1) Classification of Environmental Impact. The CML 2001 Mid-point Type Method, developed by the Centre for Environmental Sciences at Leiden University in the Netherlands [33], divides environmental impact types into three categories: (1) consumption of materials and energy, including abiotic and living resources; (2) environmental pollution, including acidification, eutrophication, ecological toxicity, human toxicity, and enhancement of greenhouse effect;

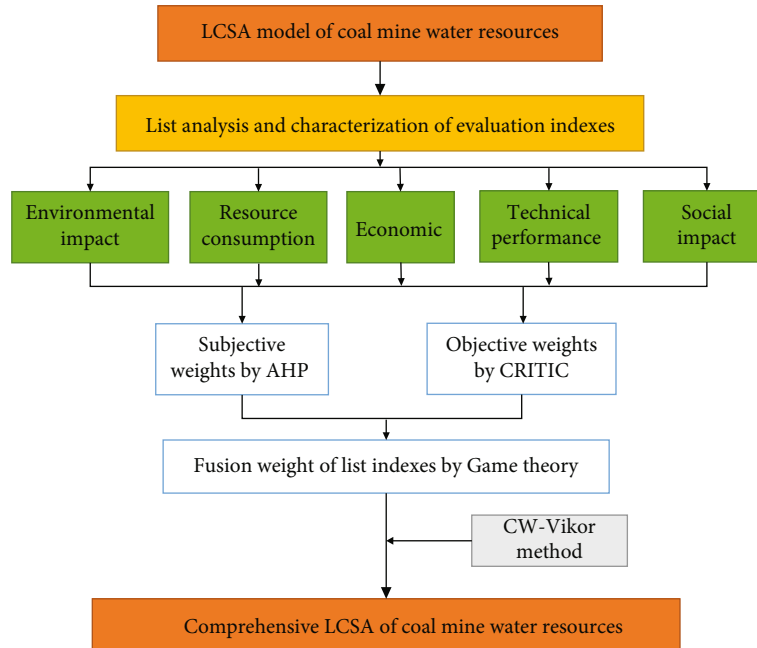


FIGURE 2: Methodology flow chart.

TABLE 1: Classification of environmental impacts and sources of pollutants.

Classification	Associated pollutant	Source
Global warming	CO ₂	Power supply, sludge disposal
	CH ₄	Power supply, sludge disposal
	NO _x	Sludge disposal
	N ₂ O	Sludge disposal
Acidification	SO ₂	Power supply, sludge disposal
	NO _x	Sludge disposal
	NH ₃	Sludge disposal
	COD	Waste water discharge, sludge disposal
Eutrophication	NH ₃ -N	Waste water discharge, sludge disposal
	BOD ₅	Waste water discharge
	TP	Sludge disposal
	TN	Sludge disposal
Human toxicity	CO	Power supply, sludge disposal
	NO _x	Power supply, sludge disposal
	Heavy metals (Hg, Cr, Pb, etc.)	Power supply, sludge disposal

and (3) environmental damage. The discharge of pollutants of coal mine water resources mainly includes power production, waste water discharge, and domestic sludge landfill disposal. In this paper, global warming potential, acidification potential, eutrophication potential, and human toxicity were selected and analyzed (Table 1).

(2) *Characteristics of Environmental Impact and Index Standardization.* Considering that pollutants include various phases, such as waste gas, waste water, and waste solids, the equivalent coefficient method is adopted for lifecycle assessment. The characterization and index standardization

of each classification of environmental impacts are shown in Appendix A.

3.2.2. *Resource Consumption List.* Four indexes were selected to evaluate water resource utilization efficiency, including water resource utilization rate, fresh water supply ratio, industrial water reuse rate, and water consumption per ten thousand industrial added value.

Water resource utilization rate reflects the degree of water resources development and utilization. It is the percentage of the regional water utilization in the total available water resources. The amount of regional water utilization

includes the consumption of Yellow River water, groundwater, and reclaimed water.

$$U_{ti} = \frac{S_{ur} + G_{rd} + C_{yc}}{T_{ol}} \times 100\%, \quad (1)$$

where U_{ti} denotes water resource utilization rate (%), S_{ur} denotes the consumption of Yellow River water (m^3), G_{rd} denotes the consumption of groundwater (m^3), C_{yc} denotes the consumption of reclaimed water ($\times 10^4 m^3$), and T_{ol} denotes the amount of total available water resources in the research area (m^3).

Fresh water supply ratio refers to the proportion of the total fresh water consumption of each water use unit in the total water supply in the research area. It reflects the dependence degree of the research area on Yellow River water and groundwater.

3.2.3. Economic List. The economic list consists of three types: resource acquisition cost, operation cost, and economic benefit.

(1) *Resource Acquisition Cost.* Resource acquisition cost refers to the cost of water resources that need to be purchased during system operation.

(2) *Operating Cost.* Operation cost includes the sum of electricity, material, engineering cost, outsourced maintenance fee, safety fee, commuting fee, business contract fee, and labor fee paid during the operation of mine water system, domestic and industrial water system, underground water system, and reuse water system, etc.

(3) *Economic Benefit.* The economic benefit mainly includes the saved water resource purchasing fee through the reclaimed water reuse project and the saved environmental protection tax when the enterprise's wastewater is treated to meet the discharge standard.

$$C_3 = C_{re} + C_{tax} = P \times Q + \frac{eq}{V_p} \times T, \quad (2)$$

where C_3 denotes system economic benefit, C_{re} denotes the saved water resource purchasing fee, C_{tax} denotes the saved environmental protection tax, P denotes the price of Yellow River water, Q denotes reclaimed water reuse amount, eq denotes pollutant equivalent index, V_p denotes discharge water quality, and T denotes environmental protection tax.

The price of Yellow River water is 3.903 Yuan/ m^3 . The pollutant equivalent index of SS, COD, NH_3-N , and BOD_5 is 4kg, 1kg, 0.8kg and 0.5kg, respectively. The environmental protection tax for each pollution equivalent of water pollutants is 2.1 Yuan.

3.2.4. Technical Performance List. The quantitative indexes of technical performance include average annual hydraulic load, suspended matter removal amount, COD removal amount, and NH_3-N removal amount. The qualitative index

is process stability. They were selected for quantitative measurement and objective description respectively.

Average annual hydraulic load refers to the percentage of the annual actual sewage treatment volume and the annual designed total sewage treatment volume. Process stability represents the adaptability of the water system to changes in water quantity and quality. It is quantified according to the scoring standard in Table 2.

3.2.5. Social Impact List. The contribution to labor positions during water resource system operation is used as the evaluation index of social impact. Meanwhile, perfection of the management system and conformation to environmental regulations are also taken as constraint indicators.

Contribution to labor positions refers to the number of labor posts during the operation of the clean water system, underground water treatment system, industrial and domestic sewage treatment system, and reuse water system. Perfection of the management system denotes whether the enterprise has a sound management organization and system of the water resource system. Conformation to environmental regulations refers to whether the production and operation of the water resource system conform to national and local environmental laws and regulation.

Perfection of the management system and conformation to environmental regulations are quantified using the scoring criteria in Table 3.

3.3. Comprehensive Evaluation of Water Resource Life Cycle Sustainability. A hierarchical model was established according to above evaluation indexes to conduct quantitative and qualitative evaluation. The evaluation steps included (1) classification according to evaluation index types (see Table 4). (2) Characterization: the evaluation indexes in each impact category are summarized. In order to eliminate the dimensionless inconsistency of variables, the range standardization method is used to process them and convert them into a unified computing unit. (3) Quantification: in this paper, the analytic hierarchy process (AHP) and CRITIC method are used to calculate the weight of each index of mining water resources. Then, the fusion weight is determined according to the game theory method. (4) Life cycle assessment: the CW-VIKOR method was used to evaluate the comprehensive utility value of the sustainability of regional water resources life cycle. The implementation process of steps (B.2)-(B.5) is shown in Appendix B.

4. Results and Discussions

4.1. Water Resource Life Cycle List Analysis

4.1.1. Environmental Impact List Analysis. The assessment of the environmental impact potential of water resources in the study area includes the following three aspects: (1) power is the main energy input. Actual power consumption data is obtained. (2) Sewage discharge: the average monitoring data of water quality of sewage treatment stations are adopted. (3) Sludge output: domestic sludge is transported to coal mine dumps for treatment. Only the environmental impact of safe

TABLE 2: Scoring criteria.

Index	10~8	8~6	6~4	4~2	2~0
Process stability	Strong	Slightly strong	General	Weak	Weaker

TABLE 3: Scoring criteria.

Index	10~8	8~6	6~4	4~2	2~0
Perfection of the management system	Perfect	Good	General	Weak	Poor
Conformation to environmental regulations	Perfect	Good	General	Weak	Poor

TABLE 4: Evaluation system of water resource life cycle sustainability in research area.

Target layer (A)	Criteria Layer (B)	Index layer (C)	Index direction	Index properties	
Water life cycle sustainability (A)	Resource Consumption (B ₁)	Water resource utilization rate (C ₁₁)	Negative	Quantitative	
		Proportion of fresh water in water supply (C ₁₂)	Negative	Quantitative	
		Water consumption per ten thousand industrial value added (C ₁₃)	Negative	Quantitative	
		Reuse rate of industrial water (C ₁₄)	Positive	Quantitative	
	Economy (B ₂)	Resource acquisition cost (C ₂₁)	Negative	Quantitative	
		Operating cost (C ₂₂)	Negative	Quantitative	
		Economic benefit (C ₂₃)	Positive	Quantitative	
		Annual average hydraulic load (C ₃₁)	Negative	Quantitative	
	Technical Performance (B ₃)	Process stability (C ₃₂)	Positive	Qualitative	
		Suspended solids removal amount (C ₃₃)	Positive	Quantitative	
		COD removal amount (C ₃₄)	Positive	Quantitative	
		Ammonia nitrogen removal capacity (C ₃₅)	Positive	Quantitative	
	Social Impact (B ₄)	Contribution to labor positions (C ₄₁)	Positive	Quantitative	
		Environmental laws and regulations (C ₄₂)	Positive	Qualitative	
		Perfection of management system (C ₄₃)	Positive	Qualitative	
	Environmental Impact (B ₅)	Global warming (C ₅₁)	Negative	Quantitative	
		Water eutrophication (C ₅₂)	Negative	Quantitative	
		Acidizing (C ₅₃)	Negative	Quantitative	
			Human toxicity (C ₅₄)	Negative	Quantitative

TABLE 5: The data of the environmental impact list.

No.	Items	Unit	2015 year	2016 year	2017 year	2018 year
1	Water resources quantity	×10 ⁴ m	753.25	548.99	537.11	492.59
2	Power	×10 ⁴ Kwh/a	610.48	556.76	518.18	932.72
3	Domestic sludge	t/a	268.32	201.83	234.15	97.55
4	SS	t/a	0.64	0.60	0.70	0.79
5	COD	t/a	97.50	34.45	60.38	34.76
6	NH ₃ -N	t/a	4.07	1.42	2.56	1.84
7	BOD ₅	t/a	43.04	16.71	24.30	16.94

landfill disposal of domestic sludge is estimated here. The data of the environmental impact list are shown in Table 5 [34].

4.1.2. Analysis of Driving Factors of Environmental Impact. According to the CML 2001 classification method, environ-

mental impact potential values were calculated and shown in Table 6 [34]. The normalization results of environmental impact potential are shown in Table 7.

From Tables 6 and 7, it can be seen that the main sources of environmental impacts include power consumption,

TABLE 6: Environmental impact potential values. PC: power consumption; DSL: domestic sludge landfill; STSD: sewage treatment station drainage.

Type	Unit	2015		2016		2017		2018	
		PC	DSL	PC	DSL	PC	DSL	PC	DSL
GWP	$\times 10^6$ kgCO ₂ eq	6.44	0.13	5.87	0.09	5.46	0.11	9.83	0.05
AP	$\times 10^4$ kgSO ₂ eq	1.98	<0.01	1.80	<0.01	1.68	<0.01	3.02	<0.01
HTP	$\times 10^5$ kg1,4-DCBeq	2.13	0.12	1.94	0.09	1.81	0.10	3.26	0.04
Type	Unit	STSD	DSL	STSD	DSL	STSD	DSL	STSD	DSL
EP	$\times 10^4$ kgPO ₄ ³⁻ eq	1.79	<0.01	0.63	<0.01	1.12	<0.01	0.78	<0.01

TABLE 7: Normalization results of environmental impact potential values.

Type	2015	2016	2017	2018	Normalization value
GWP	1.58E-07	1.44E-07	1.34E-07	2.38E-07	4.15E+13
AP	5.91E-08	5.39E-08	5.02E-08	9.02E-08	3.35E+11
EP	1.36E-07	4.77E-08	8.49E-08	5.94E-08	1.32E+11
HTP	3.97E-09	3.59E-09	3.37E-09	5.82E-09	5.67E+13

regional drainage, and landfill disposal of domestic sludge. Power consumption has the largest environmental impact, accounting for about 73%, regional drainage accounts for about 26%, and domestic sludge landfill accounts for about 1%. The main influence types are global warming, acidification, eutrophication, and human toxicity. Global warming has the greatest impact potential, accounting for about 40%-60% of all types. The second is eutrophication and acidification, accounting for 15%-38% and 17%-23%, respectively. The last is human toxicity, accounting for 1%. Global warming, acidification, and human toxicity potential are highly synchronized with power consumption. From 2015 to 2017, these three environmental indicators gradually decreased. In 2018, with the increase of regional water consumption, the energy consumption of system operation also increased, leading to a significant influence on environment.

4.1.3. *Resource Consumption List Analysis.* The method described above was used for resource consumption list analysis. The results are shown in Table 8 [34].

4.1.4. *Economic List Analysis.* The saved water resource purchasing fee from 2015 to 2018 was 17.7563 million yuan, 27.2691 million yuan, 24.26300 million yuan, and 27.2831 million yuan respectively. The saved environmental protection tax was 0.37 million yuan, 0.59 million yuan, 0.44million yuan, and 0.47million yuan, respectively. Table 9 illustrates the calculated evaluation index values of economic list [34].

4.1.5. *Technical Performance List Analysis.* Table 10 shows the statistics of technical performance index of water treatment of the 5 sewage treatment stations [34]. The comprehensive statistical results of the technical performance indexes are shown in Table 11 [34].

4.1.6. *Social Impact List Analysis.* The social impact index values are shown in Table 12 [34].

4.2. *Fusion Weight of List Indexes.* First, the subjective and objective weights of evaluation indexes in above list analysis are determined by using the AHP method and CRITIC method respectively. Then, the subjective and objective weights are fused by game theory to obtain a balanced and coordinated fusion weight. The weights obtained by AHP, CRITIC ,and game theory are represented by α , β , and γ , respectively.

4.2.1. *Subjective Weights by AHP.* On the basis of above hierarchical evaluation model, the AHP method is used to make pairwise comparison and score the indexes by expert decision. α_{A-B} represents the weight of the criterion layer (layer B) to the target layer (layer A). The weight of index to the criterion layer and consistency check is shown in Table 13. It can be seen that the CR value of the consistency ratio of the judgment matrix is all less than 0.1. The consistency test results meet the requirements.

Subjective weight of evaluation index layer (layer C) to target layer (layer A) is $\alpha_{A-C} = \{0.0909, 0.0909, 0.0909, 0.0909, 0.0165, 0.0826, 0.0826, 0.0097, 0.0766, 0.0494, 0.0231, 0.0231, 0.0130, 0.0390, 0.0390, 0.0727, 0.0364, 0.0364, 0.0364\}^T$.

4.2.2. *Objective Weights by CRITIC.* The CRITIC method is a method to deal with objective weight based on the variability and conflict among indicators. Standard deviation is used to reflect the degree of variation of data information. The larger the positive correlation coefficient of sample information, the smaller the conflict. The smaller the information difference of evaluation index, the smaller the weight of the index. In accordance with the measured data, CRITIC assigns different weights to the indexes without being affected by subjective factors. The specific calculation process of CRITIC method is shown in Appendix B 2.2.

By normalizing the original list data, the decision matrix of standardized evaluation indexes was obtained (Table 14). Then, the Pearson correlation coefficient and standard deviation among the evaluation indexes are solved (Tables 15

TABLE 8: The value of water resource consumption index.

Item	2015	2016	2017	2018
Water utilization rate (%)	60.61	68.85	61.28	65.00
Fresh water supply ratio (%)	62.31	44.74	46.35	41.34
Industrial water reuse rate (%)	37.69	55.26	53.65	58.66
Water consumption per ten thousand industrial added value (m ³ /10000 Yuan)	21.05	23.15	18.21	16.11

TABLE 9: Evaluation index values of economic list.

Item	2015	2016	2017	2018
Resource acquisition cost (Yuan)	2464.16	1799.49	1753.02	1524.56
Operating cost (Yuan/m ³)	2.39	2.24	2.18	2.77
Economic benefit (Yuan)	1812.75	2786.09	2469.95	2774.82

TABLE 10: Statistics of technical performance index of water treatment.

Water treatment unit	Technical index	2015	2016	2017	2018
Anjialing domestic sewage treatment station	Average annual hydraulic load (%)	52	36	54	19
	Suspended matter removal amount (t/a)	827.54	587.72	888.39	280.01
	COD removal amount (t/a)	59.11	28.63	59.54	21.50
	NH ₃ -N removal amount (t/a)	3.77	2.53	3.77	1.16
Antaipo terminal sewage treatment station	Average annual hydraulic load (%)	54	64	52	62
	Suspended matter removal amount (t/a)	371.10	453.40	361.66	385.16
	COD removal amount (t/a)	28.16	26.62	22.43	25.43
	NH ₃ -N removal amount (t/a)	1.82	1.96	1.39	1.72
Underground water treatment station (No. A) of Jinggong mine	Average annual hydraulic load (%)	102	42	56	14
	Suspended matter removal amount (t/a)	8868.07	3078.89	4218.73	1079.44
	COD removal amount (t/a)	187.60	63.85	96.87	25.77
	NH ₃ -N removal amount (t/a)	2.23	1.07	1.30	0.33
Underground water treatment station (No. B) of Jinggong mine	Average annual hydraulic load (%)	23	25	29	39
	Suspended matter removal amount (t/a)	3405.30	3874.25	4898.50	5252.58
	COD removal amount (t/a)	67.85	64.49	68.65	101.45
	NH ₃ -N removal amount (t/a)	0.76	1.16	1.24	1.71
Anjialing terminal sewage treatment station	Average annual hydraulic load (%)	107	98	92	89
	Suspended matter removal amount (t/a)	8771.60	6005.00	5674.88	6183.61
	COD removal amount (t/a)	224.56	209.77	183.21	189.63
	NH ₃ -N removal amount (t/a)	4.65	4.21	4.29	3.62

TABLE 11: Technical performance index value.

Item	2015	2016	2017	2018
Annual hydraulic load (%)	67	53	57	45
Process stability (point)	6	6	7	8
Suspended matter removal amount (t/a)	22243.61	13999.26	16042.17	13180.80
COD removal amount (t/a)	567.28	393.36	430.71	363.78
NH ₃ -N removal amount (t/a)	13.23	10.93	11.99	8.55

TABLE 12: Social impact index value.

Item	2015	2016	2017	2018
Contribution to labor positions (unit)	199	199	199	232
Conformation to environmental regulations (point)	7	7	8	8
Perfection of management system (point)	6	6	7	8

TABLE 13: Weight of index to criterion layer and consistency check.

Layer	Judgment matrix						Weight	Consistency check
A-B	A	B ₁	B ₂	B ₃	B ₄	B ₅	α_{A-B}	$CR_{A-B} = 0$
	B ₁	1	2	2	4	2	0.3636	
	B ₂	0.5	1	1	2	1	0.1818	
	B ₃	0.5	1	1	2	1	0.1818	
	B ₄	0.25	0.5	0.5	1	0.5	0.1818	
	B ₅	0.5	1	1	2	1	0.0909	
B ₁ -C ₁	B ₁	C ₁	C ₂	C ₃	C ₄		α_{B_1-C}	$CR_{B_1-C_1} = 0$
	C ₁₁	1	1	1	1		0.2500	
	C ₁₂	1	1	1	1		0.2500	
	C ₁₃	1	1	1	1		0.2500	
	C ₁₄	1	1	1	1		0.2500	
B ₂ -C ₂	B ₂	C ₅	C ₆	C ₇			α_{B_2-C}	$CR_{B_2-C_2} = 0$
	C ₂₁	1	0.2	0.2			0.0909	
	C ₂₂	5	1	1			0.4545	
	C ₂₃	5	1	1			0.4545	
B ₃ -C ₃	B ₃	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	α_{B_3-C}	$CR_{B_3-C_3} = 0.0457$
	C ₃₁	1	0.2	0.2	0.33	0.33	0.0535	
	C ₃₂	5	1	3	3	3	0.4214	
	C ₃₃	5	0.33	1	3	3	0.2715	
	C ₃₄	3	0.33	0.33	1	1	0.1268	
	C ₃₅	3	0.33	0.33	1	1	0.1268	
B ₄ -C ₄	B ₄	C ₁₃	C ₁₄	C ₁₅			α_{B_4-C}	$CR_{B_4-C_4} = 0$
	C ₄₃	1	0.33	0.33			0.1429	
	C ₄₂	3	1	1			0.4286	
	C ₄₁	3	1	1			0.4286	
B ₅ -C ₅	B ₅	C ₁₆	C ₁₇	C ₁₈	C ₁₉		α_{B_5-C}	$CR_{B_5-C_5} = 0$
	C ₅₁	1	0.5	1	1		0.4000	
	C ₅₂	0.5	1	2	2		0.2000	
	C ₅₃	1	0.5	1	1		0.2000	
	C ₅₄	1	0.5	1	1		0.2000	

and 16). Finally, the objective weight is determined by CRITIC as shown in Table 17.

$$\begin{bmatrix} 0.0689 & 0.0519 \\ 0.0519 & 0.0537 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} 0.0689 \\ 0.0537 \end{bmatrix}. \quad (3)$$

4.2.3. *Fusion Weights by Game theory.* According to the subjective weight and objective weight, the first-order derivative of optimization is carried out:

The linear combination coefficients $\alpha_1 = 0.9073$ and $\alpha_2 = 0.1230$ were calculated. The optimal weight vector combination

TABLE 14: Decision matrix of standardized evaluation indexes.

	2015	2016	2017	2018
C_{11}	1.0000	0.0000	0.9180	0.4670
C_{12}	0.0000	0.8376	0.7608	1.0000
C_{13}	0.0000	0.8376	0.7608	1.0000
C_{14}	0.3405	0.0000	0.7196	1.0000
C_{21}	0.0000	0.7074	0.7569	1.0000
C_{22}	0.6440	0.9071	1.0000	0.0000
C_{23}	0.0000	1.0000	0.6752	0.9884
C_{31}	0.0000	0.6398	0.4710	1.0000
C_{32}	0.0000	0.0000	0.5000	1.0000
C_{33}	1.0000	0.0903	0.3157	0.0000
C_{34}	1.0000	0.1454	0.3289	0.0000
C_{35}	1.0000	0.5096	0.7354	0.0000
C_{43}	0.0000	0.0000	0.0000	1.0000
C_{42}	0.0000	0.0000	0.5000	1.0000
C_{41}	0.0000	0.0000	0.5000	1.0000
C_{51}	0.7704	0.9091	1.0000	0.0000
C_{52}	0.7769	0.9071	1.0000	0.0000
C_{53}	0.0000	1.0000	0.5773	0.8672
C_{54}	0.7554	0.9137	1.0000	0.0000

coefficients $\alpha_1^* = 0.8806$ and $\alpha_2^* = 0.1194$ were obtained by normalizing α_1 and α_2 . The game theory fusion weight of the evaluation index on the target layer is obtained as follows: $\gamma_{A-C} = \alpha_1^* \omega_1 + \alpha_2^* \omega_2 = \{0.0870, 0.0853, 0.0853, 0.0855, 0.0195, 0.0795, 0.0785, 0.0137, 0.0733, 0.0515, 0.0281, 0.0275, 0.0183, 0.0402, 0.0402, 0.0710, 0.0391, 0.0377, 0.0390\}^T$.

In the same way, the game theory fusion weight value of the evaluation index for the rule layer is obtained: $\gamma_{B1-C1} = \{0.3031, 0.2295, 0.2295, 0.2379\}^T$, $\gamma_{B2-C2} = \{0.0355, 0.4747, 0.4897\}^T$, $\gamma_{B3-C3} = \{0.0610, 0.4023, 0.2687, 0.1347, 0.1332\}^T$, $\gamma_{B4-C4} = \{0.1841, 0.4080, 0.4080\}^T$, and $\gamma_{B5-C5} = \{0.4036, 0.1983, 0.1997, 0.1984\}^T$.

4.3. Comprehensive Assessment of Water Resource Life Cycle Sustainability. The VIKOR method is a common and useful multicriteria decision-making technique that is used to determine a compromise alternative. The VIKOR method has the advantages of considering the maximization of group utility (S_i), the minimization of individual regret (R_i), and the subjective preferences of decision-makers and therefore has higher stability and credibility for ranking compared to other methods [35]. According to the calculation steps of CW-VIKOR in Appendix B, the fusion weight γ was used to calculate the group utility value S_i , individual regret value R_i , and comprehensive utility value Q_i , respectively. Then, we sorted them by size. The smaller the Q_i value is, the better the sustainable utilization of water resources in the life cycle.

4.3.1. Evaluation Results of Each Subsystem

(1) *Comprehensive Evaluation of Resource Consumption.* The positive and negative ideal solutions of resource consumption index are $P^* = (1,1,1,1)$ and $P^- = (0,0,0,0)$, respectively. The calculated S_i , R_i , and Q_i value of the resource consumption subsystem is shown in Table 18.

The results show that the ranking result of Q_i is 2017 > 2018 > 2015 > 2016. The water utilization rate and water consumption per ten thousand industrial added value in 2016 were the highest, leading to low water utilization efficiency. The reason is that after 2016, the coal industry reduced the consumption of water resources; so, the regional water use efficiency increased from 2017 to 2018.

Although water use efficiency in the study area has been increasing in recent years, the reuse rate of industrial water is still low. There is still a large room for improvement. In general, the demand for fresh water used for production in the research area is gradually replaced by reclaimed water.

(2) *Economic Comprehensive Evaluation.* The positive and negative ideal solutions of the economic index are $P^* = (1,1,1)$ and $P^- = (0,0,0)$ respectively. The calculated S_i , R_i , and Q_i value of the economic subsystem is shown in Table 19.

The results show that the ranking result of Q_i is 2016 > 2017 > 2018 > 2015. From 2016 to 2017, their Q_i values are relatively low, which is due to the relatively low operating cost of the system. Meanwhile, the saved water resource purchasing fee and the saved environmental protection tax by water reuse project have relatively high contribution to economic benefits. In 2018, in order to improve the stability of the operation system, the coal enterprise increased the investment for the operation and maintenance of the water system. The labor cost, material cost, and business contract fee also increased. So, the operation cost increased.

(3) *Comprehensive Evaluation of Technical Performance.* The positive and negative ideal solutions of the technical performance index are $P^* = (1,1,1,1)$ and $P^- = (0,0,0,0)$, respectively. The calculated S_i , R_i , and Q_i value of the technical performance subsystem is shown in Table 20.

The results show that the ranking result of Q_i is 2017 > 2018 > 2015 > 2016. From 2017 to 2018, their Q_i values were relatively low, and the water system operated stably. While in 2016, the system operated in a relatively poor state. The manifestation is the serious siltation of coal slime in the presettling adjusting tank. The main reason is that Anjialing Terminal sewage treatment station has frequently appeared problems since November 2015. The underground water treatment system (No. B) of Jinggong No.1 Mine is unable to discharge mud due to the high suspended matter, which affects the operation and the water quality of the effluent. After 2017, with the decrease of coal production capacity and the well closure of Jinggong No.2 Mine, the amount of waste water generated by regional production decreases.

TABLE 15: Correlation coefficient of Pearson between evaluation indexes.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{51}	C_{52}	C_{53}	C_{54}
C_{11}	1	-0.624	-0.624	0.396	-0.516	0.066	-0.781	-0.625	0.048	0.721	0.691	0.573	-0.187	0.048	0.048	0.144	0.150	-0.850	0.130
C_{12}	-0.624	1	1.000**	0.359	0.990*	-0.227	0.975*	0.945	0.636	-0.991**	-0.994**	-0.834	0.526	0.636	0.636	-0.359	-0.366	0.939	-0.342
C_{13}	-0.624	1.000**	1	0.359	0.990*	-0.227	0.975*	0.945	0.636	-0.991**	-0.994**	-0.834	0.526	0.636	0.636	-0.359	-0.366	0.939	-0.342
C_{14}	0.396	0.359	0.359	1	0.489	-0.634	0.167	0.463	0.936	-0.264	-0.314	-0.515	0.740	0.936	0.936	-0.665	-0.665	0.041	-0.665
C_{21}	-0.516	0.990*	0.990*	0.489	1	-0.297	0.936	0.949	0.735	-0.965*	-0.976*	-0.851	0.595	0.735	0.735	-0.426	-0.433	0.882	-0.410
C_{22}	0.066	-0.227	-0.227	-0.634	-0.297	1	-0.184	-0.525	-0.705	0.237	0.275	0.713	-0.942	-0.705	-0.705	0.990**	0.989*	-0.124	0.993**
C_{23}	-0.781	0.975*	0.975*	0.167	0.936	-0.184	1	0.926	0.486	-0.995**	-0.988*	-0.819	0.459	0.486	0.486	-0.312	-0.319	0.992**	-0.294
C_{31}	-0.625	0.945	0.945	0.463	0.949	-0.525	0.926	1	0.744	-0.950*	-0.963*	-0.969*	0.758	0.744	0.744	-0.635	-0.642	0.884	-0.621
C_{32}	0.048	0.636	0.636	0.936	0.735	-0.705	0.486	0.744	1	-0.569	-0.612	-0.778	0.870	1.000**	1.000**	-0.770	-0.772	0.375	-0.764
C_{33}	0.721	-0.991**	-0.991**	-0.264	-0.965*	0.237	-0.995**	-0.950*	-0.569	1	0.999**	0.849	-0.518	-0.569	-0.569	0.365	0.373	-0.974*	0.348
C_{34}	0.691	-0.994**	-0.994**	-0.314	-0.976*	0.275	-0.988*	-0.963*	-0.612	0.999**	1	0.868	-0.556	-0.612	-0.612	0.403	0.410	-0.961*	0.386
C_{35}	0.573	-0.834	-0.834	-0.515	-0.851	0.713	-0.819	-0.969*	-0.778	0.849	0.868	1	-0.882	-0.778	-0.778	0.800	0.805	-0.774	0.789
C_{41}	-0.187	0.526	0.526	0.740	0.595	-0.942	0.459	0.758	0.870	-0.518	-0.556	-0.882	1	0.870	0.870	-0.978*	-0.980*	0.384	-0.975*
C_{42}	0.048	0.636	0.636	0.936	0.735	-0.705	0.486	0.744	1.000**	-0.569	-0.612	-0.778	0.870	1	1.000**	-0.770	-0.772	0.375	-0.764
C_{43}	0.048	0.636	0.636	0.936	0.735	-0.705	0.486	0.744	1.000**	-0.569	-0.612	-0.778	0.870	1.000**	1	-0.770	-0.772	0.375	-0.764
C_{51}	0.144	-0.359	-0.359	-0.665	-0.426	0.990**	-0.312	-0.635	-0.770	0.365	0.403	0.800	-0.978*	-0.770	-0.770	1	1.000**	-0.249	1.000**
C_{52}	0.150	-0.366	-0.366	-0.665	-0.433	0.989*	-0.319	-0.642	-0.772	0.373	0.410	0.805	-0.980*	-0.772	-0.772	1.000**	1	-0.256	1.000**
C_{53}	-0.850	0.939	0.939	0.041	0.882	-0.124	0.992**	0.884	0.375	-0.974*	-0.961*	-0.774	0.384	0.375	0.375	-0.249	-0.256	1	-0.231
C_{54}	0.130	-0.342	-0.342	-0.665	-0.410	0.993**	-0.294	-0.621	-0.764	0.348	0.386	0.789	-0.975*	-0.764	-0.764	1.000**	1.000**	-0.231	1

**—at the 0.01 level (double-tailed), the correlation was significant; *—at the 0.05 level (double-tailed), the correlation was significant.

TABLE 16: Standard deviation between evaluation indexes.

Index	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}
Standard deviation	0.46	0.44	0.44	0.44	0.43	0.45	0.47	0.42	0.48	0.45
Index	C_{34}	C_{35}	C_{41}	C_{42}	C_{43}	C_{51}	C_{52}	C_{53}	C_{54}	
Standard deviation	0.44	0.42	0.50	0.48	0.48	0.46	0.46	0.44	0.46	

TABLE 17: Weight of evaluation indexes.

Target layer (A)	Rule layer (B)	Index layer (C)	β_{B-C}	β_{A-C}
Water life cycle sustainability	Resource consumption (0.1917)	Water utilization rate (C_{11})	0.3031	0.0581
		Fresh water supply ratio (C_{12})	0.2295	0.0440
		Water consumption per ten thousand industrial added value (C_{13})	0.2295	0.0440
		Industrial water reuse rate (C_{14})	0.2379	0.0456
	Economy (0.1468)	Resource acquisition cost (C_{21})	0.2854	0.0419
		Operating cost (C_{22})	0.3835	0.0563
		Economic benefit (C_{23})	0.3311	0.0486
		Average annual hydraulic load (C_{31})	0.1520	0.0431
	Technical performance (0.2836)	Process stability (C_{32})	0.1717	0.0487
		Suspended matter removal amount (C_{33})	0.2352	0.0667
		COD removal amount (C_{34})	0.2306	0.0654
		NH ₃ -N removal amount (C_{35})	0.2105	0.0597
		Contribution to Labor Position (C_{41})	0.3700	0.0572
		Social impact (0.1546)	Conformation to environmental regulations (C_{42})	0.3150
Perfection of the management system (C_{43})	0.3150		0.0487	
Global warming (C_{51})	0.2629		0.0587	
Environmental impact (0.2233)	Water eutrophication (C_{52})		0.2633	0.0588
	Acidification (C_{53})	0.2118	0.0473	
	Human toxicity (C_{54})	0.2620	0.0585	

TABLE 18: S_i , R_i , and Q_i value of the resource consumption subsystem.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	0.6159	4	0.2295	3	0.8443	3
2016	0.6155	3	0.3031	4	0.9996	4
2017	0.2014	2	0.0667	1	0.0438	1
2018	0.1616	1	0.1616	2	0.2006	2

TABLE 19: S_i , R_i , and Q_i value of economic subsystem.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	0.6942	4	0.4897	4	1.0000	4
2016	0.0545	1	0.0441	1	0.0000	1
2017	0.1677	2	0.1591	2	0.2174	2
2018	0.4804	3	0.4747	3	0.8160	3

Therefore, the removal of pollutants decreases, and the Q_i value of the technical subsystem decreases accordingly.

The treatment of domestic sewage in the mining area is relatively stable while the treatment of industrial and underground sewage is relatively complex. The removal rate of

TABLE 20: S_i , R_i , and Q_i value of technical performance subsystem.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	0.4633	3	0.4023	3	0.5000	3
2016	0.8491	4	0.4023	4	1.0000	4
2017	0.5429	2	0.2012	1	0.1032	1
2018	0.5366	1	0.2687	2	0.2629	2

suspended matter in underground water treatment station is high, but the process stability is poor. The reason is that the content of suspended matter in the influent is high and unstable. The annual hydraulic load of Anjialing terminal sewage treatment station is high, and the sewage source is relatively complex.

(4) *Comprehensive Evaluation of Social Impact.* The positive and negative ideal solutions of the social impact index are $P^* = (1,1,1)$ and $P^- = (0,0,0)$, respectively. The calculated S_i , R_i , and Q_i value of the social impact subsystem is shown in Table 21.

The results show that the ranking result of Q_i is 2018 > 2017 > 2016 > 2015. The overall social impact of the

TABLE 21: S_i , R_i , and Q_i value of the social impact subsystem.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	1.0001	4	0.4080	4	1.0000	4
2016	1.0001	3	0.4080	3	1.0000	3
2017	0.5921	2	0.2040	2	0.5460	2
2018	0.0000	1	0.0000	1	0.0000	1

system continues to improve. The perspective of social impact, perfection of the management system, and conformation to environmental regulations all have a significant impact on social subsystems.

From 2017 to 2018, the coal industry has successively designed the Anjialing Regional Sewage Treatment System Upgrading and Emissions Reduction Project. The industry also implemented technical transformation and optimization projects for the water supply and drainage system. It improved the system management system and the regional environmental supervision mechanism. These measures fully increased the employment opportunities.

(5) *Comprehensive Evaluation of Environmental Impact.* The positive and negative ideal solutions of the environmental impact index are $P^* = (1,1,1,1)$ and $P^- = (0,0,0,0)$, respectively. The calculated S_i , R_i , and Q_i value of the environmental impact subsystem is shown in Table 22.

The results show that the ranking result of Q_i is 2016 > 2017 > 2015 > 2018. In 2018, with the increase of system operating load and a large amount of energy input, the contribution of potential value of global warming, acidification, and human toxicity increased significantly, leading to a significant decline in the sustainability of the environmental subsystem. More than 97% of the global warming potential and 99% of the acidification potential of the system increase with power consumption. The potential of global warming and acidification can be effectively reduced by reducing system power consumption. The reuse of reclaimed water can also reduce the impact on the environment. The greater the reuse of water, the smaller the eutrophication potential. Although the environmental impact potential value of systemic domestic sludge landfill is smaller than that of other influencing factors, many studies have shown that sludge landfill is not an environmentally friendly disposal method, and enterprises should seek a relatively harmless disposal scheme.

4.3.2. *Systematic Comprehensive Evaluation Results.* According to the CW-VIKOR evaluation model, the calculated S_i , R_i , and Q_i value of water resource life cycle sustainability is shown in Table 23 and Figure 3.

The results show that the ranking result of Q_i is 2017 > 2018 > 2016 > 2015. During the research period, the Q_i value showed a decreasing trend, indicating that the sustainability of regional water resource life cycle was improved.

In 2015, the sustainability of water resource life cycle performed poorly in three aspects: economic subsystem, social

TABLE 22: S_i , R_i , and Q_i value of environmental impact subsystem.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	0.3852	3	0.1997	3	0.4295	3
2016	0.0723	1	0.0367	1	0.0000	1
2017	0.0844	2	0.0844	2	0.0731	2
2018	0.8268	4	0.4036	4	1.0000	4

TABLE 23: S_i , R_i , and Q_i value of water resource life cycle sustainability.

Year	S_i	Rank	R_i	Rank	Q_i	Rank
2015	0.6112	4	0.0853	3	0.9833	4
2016	0.4879	3	0.0870	4	0.8128	3
2017	0.2818	1	0.0366	1	0.0000	1
2018	0.3880	2	0.0795	2	0.5865	2

subsystem, and resource subsystem. In terms of resource consumption, fresh water accounted for a higher proportion of water supply (about 62.31%), while industrial water reuse rate was low (only 37.69%). On the economic side, there is less economic benefit, mainly because only a small portion of reclaimed water is returned to production water.

In 2016, the sustainability of water resources life cycle is restricted by society, technology, and resources. The water utilization rate and water consumption of ten thousand Yuan of industrial added value in this year are the main influencing indexes. Another important influence is the poor process stability. The sewage treatment system of Anjialing terminal sewage treatment station often cannot operate normally, affecting the effluent quality effect.

In 2017, the sustainability of the regional water resource life cycle was relatively strong, but there was still a large room for progress. For example, the water utilization efficiency was far from the domestic advanced level, and a large amount of recycled water was not effectively used.

In 2018, social subsystems performed well, with more professional management models, clearer functional division of labor, and improved work efficiency. With the increase of regional water consumption, operating cost, and energy consumption, the evaluation value of the environmental subsystem and economic subsystem increased obviously. In fact, energy saving and consumption reduction is an effective way to alleviate the contradiction between the increase of water quantity in operation and the increase of pollutant discharge.

4.4. *Optimization Strategy.* Based on above dynamic evaluation results, optimization strategy for continuous improvement is suggested as follows:

- (1) Continuously improve the water resources management mode. Adjusting industrial structure and adopting water-saving facilities can reduce the demand for fresh water and improve water use efficiency
- (2) Continuously improve the quality treatment and quality supply of wastewater. According to the different

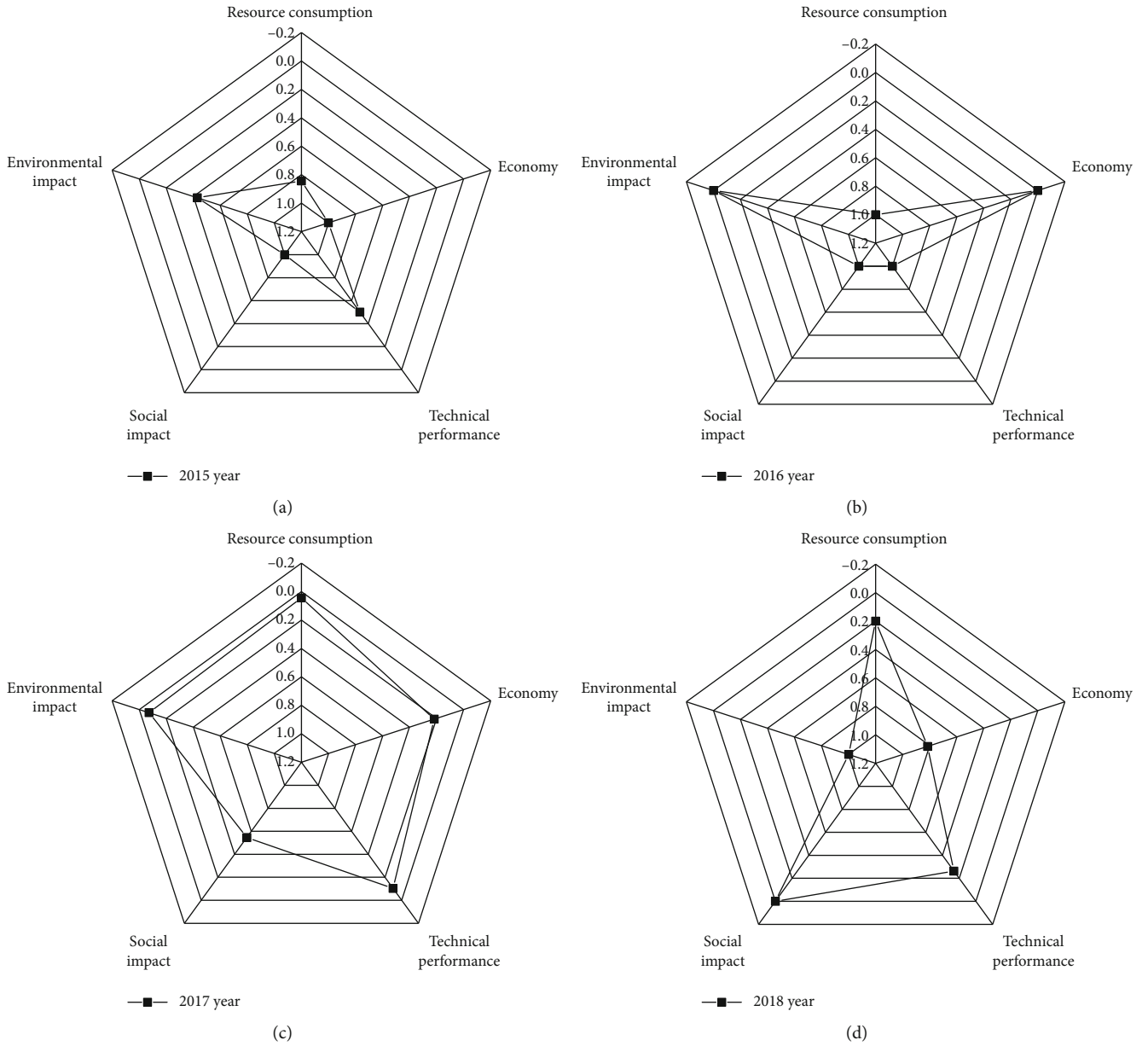


FIGURE 3: Continued.

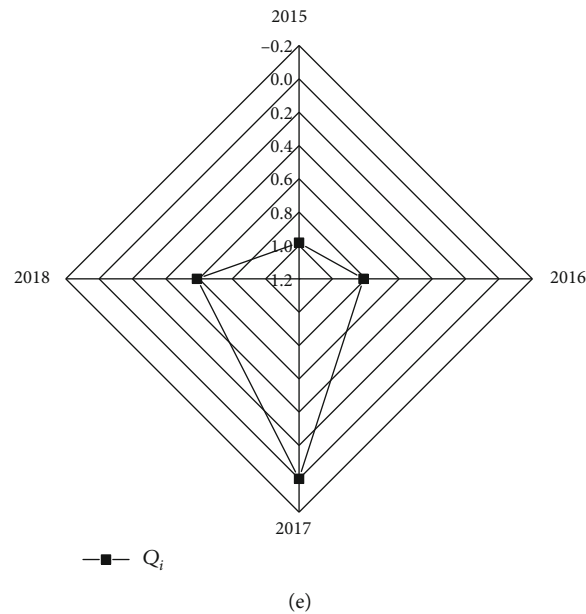


FIGURE 3: Comprehensive assessment results of water resource life cycle sustainability.

water quality requirements of different water subsystems, water users with high water quality in the upstream should be given priority. Meanwhile, water drainage should be directly supplied to water users with low water quality in the downstream. Implement the fine management of wastewater treatment and supply, reduce the input of sewage treatment system, and reuse the drainage without treatment

- (3) Continuously improve the stability of sewage treatment process. First, the source control should be carried out to reduce the concentration of suspended matter in the sewage treatment station. Second, solve the problems in the coal slime pressure and filtration of the underground water treatment station (No. B) of Jinggong No.1 mine as soon as possible. For the drainage of coal preparation plant, the closed-circuit circulation should be enhanced, and the washing intensity should be strictly controlled. Then, the serious siltation of water diversion culvert and presedimentation regulating tank should be regularly cleaned. Finally, the dredging pump should be replaced to improve the slime discharging capacity
- (4) Continue to save energy and reduce power consumption and costs

5. Conclusions

In this paper, a dynamic model was established to evaluate the water utilization efficiency in the coal mining area based on the life cycle sustainability assessment theory. The influence of five aspects (including resources, economy, technology, society, and environment) and 19 factors was considered. The game theory method was adopted to calculate the fusion weights. The CW-VIKOR method was used to explain the dynamic evaluation results of

water efficiency in the coal mining area. The main conclusions are listed as follows:

- (1) For the water resource utilization in mining area, the environmental impact mainly comes from three aspects: regional drainage, domestic sludge landfill and disposal, and water system operation power consumption. Power consumption has the greatest environmental impact, accounting for about 73%, regional drainage for about 26%, and domestic sludge landfill for about 1%
- (2) The CW-VIKOR method can coordinate the relationships among resource consumption, economy, technical performance, social impact, and environmental impact. The evaluation result is reliable and close to the actual situation
- (3) From 2015 to 2018, the comprehensive utility value of water resource life cycle sustainability in the mining area was 0.983, 0.813, 0.000, and 0.587, respectively. It indicates that the water resource life cycle sustainability ranked first in 2017 and was relatively low in 2015. It can be seen that the sustainability of water resources life cycle in this mine area has improved as a whole
- (4) More than 97% of the global warming potential and 99% of the acidification potential of the system increase with power consumption. The potential of global warming and acidification can be effectively reduced by reducing system power consumption. The reuse of reclaimed water can also reduce the impact on the environment. The greater the reuse of water, the smaller the eutrophication potential

The dynamic model established in this paper is also applicable to other coal mine areas, and only the factor

weights need to be modified according to the specific characteristics of each coal mine. It can provide guidance for optimal exploitation and allocation of coal mine water resources.

Appendix

A.

A.1. Characteristics of Environmental Impact

(1) Global Warming

Emissions of greenhouse gases such as CO₂, N₂O, and CH₄ increase the greenhouse effect. The global warming potential value was obtained by using equivalent coefficient method and taking CO₂ equivalent as reference

$$GWP = \sum_i \delta_i \times M_{GWP}, \quad (A.1)$$

where GWP denotes global warming potential (kgCO₂eq). δ_i denotes the global warming potential coefficient of greenhouse gas i (kgCO₂eq/kg). M_{GWP} denotes emission mass of greenhouse gas i (kg). The potential coefficient of GWP is shown in Table 24.

(2) Acidification

The acidification potential was obtained by converting the pollutants with the equivalent of SO₂ as reference.

$$AP = \sum_i \varepsilon_i \times M_{AP}, \quad (A.2)$$

where AP denotes acidification potential (kgSO₂eq). ε_i denotes the acidification potential coefficient of pollutant i (kgSO₂eq/kg). M_{AP} denotes the discharge mass of acidified pollutant i (kg). The AP potential coefficient is shown in Table 25.

(3) Eutrophication

The eutrophication potential value was obtained by conversion with PO₄³⁻ equivalent as reference.

$$EP = \sum_i \lambda_i \times M_{EP}, \quad (A.3)$$

where EP denotes eutrophication potential value (kgPO₄³⁻eq). λ_i denotes eutrophication potential coefficient (kgPO₄³⁻eq/kg). M_{EP} denotes discharge mass of pollutant i (kg). The EP potential coefficient is shown in Table 26.

(4) Human Toxicity

All potential contaminants that are toxic to humans are converted with 1,4-dichlorobenzene equivalent as a reference.

$$HTP = \sum_i \beta_i \times M_{HTP}, \quad (A.4)$$

where HTP denotes human toxicity potential value (kg); β_i denotes human toxicity impact potential coefficient (kg1,4-DCBeq/kg). M_{HTP} denotes discharge mass of toxic pollutant i (kg). The potential coefficient of HTP is shown in Table 27.

A.2. *Standardization of Environmental Impact Indexes.* In order to compare the impact results of different types of environment during the operation of water systems, the characteristic results need to be normalized. The standardized calculation formula is shown as (A.4) and (A.5).

$$N_i = \frac{C_i}{S_i}, \quad (A.5)$$

where N_i denotes the standardization result of index. C_i denotes the characteristic result of index. S_i denotes the standardization base value. The standard reference values in the CML 2001 method were adopted (Table 28).

B.

B.1. *Data Standardization.* In order to eliminate dimensionless inconsistency of variables, the range normalization method is used for processing, so as to obtain the standardized decision matrix $Y=[y_{ij}]_{m \times n}$. The calculation formula of standardized data, y_{ij} , is as follows:

For positive index,

$$y_{ij} = \frac{(x_{ij} - x_{ij}^{\min})}{(x_{ij}^{\max} - x_{ij}^{\min})}. \quad (B.1)$$

For reverse index,

$$y_{ij} = \frac{(x_{ij}^{\max} - x_{ij})}{(x_{ij}^{\max} - x_{ij}^{\min})}, \quad (B.2)$$

where y_{ij} is the normalized data of index j in scheme i . y_{ij} is the original data of index j in scheme i . x_{ij}^{\max} and x_{ij}^{\min} are respectively the maximum and minimum value of the original value of the evaluation index j .

B.2. *Determination of Fusion Weight.* In this paper, first, the analytic hierarchy process (AHP) and CRITIC method are respectively used to calculate the weight of each index in the evaluation system of water resources in the mining area. Then, the final fusion weight is determined according to the game theory method. The specific methods are as follows.

B.2.1. *Weight by AHP.* The order of importance of the evaluation factors was pairwise compared by the expert advisory group to establish the judgment matrix A . After quantization, check the consistency of matrix A . The application steps of this method are as follows:

TABLE 24: GWP pollutant and potential coefficient.

Pollutant	CO ₂	CH ₄	N ₂ O	CO
Potential coefficient	1	28	265	0.027

TABLE 25: AP pollutants and potential coefficients.

Pollutant	SO ₂	NO _x	NH ₃
Potential coefficient	1	0.5	1.6

TABLE 26: EP pollutant and potential coefficient.

Pollutant	COD	NH ₃ -N	BOD ₅	TP	TN
Potential coefficient	0.022	3.64	0.022	3.06	0.42

TABLE 27: HTP pollutant and potential coefficient.

Air pollutant	CO		NH ₃		NO _x			PM10		
Potential coefficient	0.012		0.1		1.2			0.82		
Water pollutant	Hg	Pb	Cd	Ni	Zn	Cu	Cr	Sn	As	Se
Potential coefficient	1425.6	12.26	22.89	331.08	0.58	1.34	3.42	0.017	951	56011
Soil pollutant	Hg	Pb	Cd	Ni	Zn	Cu	Cr	Sn		
Potential coefficient	1080.54	293.3	66.68	198.17	0.42	1.25	500	0.52		

TABLE 28: Normalization reference value of CML 2001.

Impact type	Standardization base value	Unit
Climate change (GWP100a)	4.15E+13	kgCO ₂ eq
Acidification potential	3.35E+11	kgSO ₂ eq
Eutrophication potential	1.32E+11	kgPO ₄ eq
Human toxicity (HTP100a)	5.67E+13	kg1,4-DCBeq

(1) Construction of Judgment Matrix

An n -order matrix A containing n evaluation indexes is constituted:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}. \quad (B.3)$$

The scale and meaning of the judgment matrix are shown in Table 29.

(2) Weight Vector

The maximum eigenvalue and eigenvector of the matrix are calculated according to the established judgment matrix.

In this paper, the root method is adopted to calculate the component of the eigenvector, namely, the weight value W .

Calculate the component vectors \bar{M}_i of the eigenvectors W_i of matrix A

$$\bar{M}_i = \left[\prod_{j=1}^n a_{ij} \right]^{\frac{1}{n}} \quad (i, j = 1, 2, \dots, n). \quad (B.4)$$

Normalization of \bar{M}_i will be carried out to obtain the weight vector W_i

$$W_i = \frac{\bar{M}_i}{\sum_{i=1}^n \bar{M}_i} \quad (i = 1, 2, \dots, n). \quad (B.5)$$

The maximum eigenroot value λ_{\max} is calculated according to W_i and A

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{W_i} \quad (B.6)$$

(3) Consistency Check

Hierarchy sorting consistency test was carried out. The verification coefficient CR was calculated by using the

TABLE 29: Judge the scale and meaning of the matrix.

Scale	Meaning
1	Both factors are equally important
3	The former is slightly more important than the latter
5	The former is more important than the latter
7	The former is much more important than the latter
9	The former is extremely important than the latter
2, 4, 6, 8	The median of the above adjacent judgments

average random consistency index RI (Table 30)

$$CR = \frac{CI}{RI} = \frac{\lambda_{\max}}{n-1} / RI, \quad (B.7)$$

where n is the number of single-level participation evaluation indicators.

B.2.2. Weight by the CRITIC Method

- (1) Determine the standard deviation σ of different index

$$\sigma = \sqrt{\frac{1}{m} \sum_{i=1}^m (a_i - \bar{a})^2}, \quad (B.8)$$

where m is the number of samples of the same index. a_i is the index value of the i th sample. \bar{a} is the average value of m samples.

- (2) Determine the conflict representative value ρ_{ab} between indices a and b

$$\rho_{ab} = \frac{\sum_{i=1}^m (a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^m (a_i - \bar{a})^2} \sqrt{\sum_{i=1}^m (b_i - \bar{b})^2}}, \quad (B.9)$$

$$\eta_{ab} = 1 - \rho_{ab}$$

where ρ_{ab} is the correlation coefficient of a and b . b_i is the index value of the i th sample. \bar{b} is the average value of m samples. η_{ab} is the conflict value between a and b .

- (3) Calculate information value

$$G_i = \sigma \sum_{i=1}^m (1 - \rho_{ij}), \quad (B.10)$$

where ρ_{ij} is the correlation coefficient of index i and index j .

- (4) Calculate the weight value of index i

TABLE 30: Consistency index RI.

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$W_i = \frac{G_i}{\sum_{i=1}^n G_i}. \quad (B.11)$$

B.2.3. Fusion Weight by Game Theory

- (1) The vector composed of the weights of L indexes is

$$u(k) = \{u_{k1}, u_{k2}, \dots, u_{kn}\} \{k = 1, 2, \dots, L\}. \quad (B.12)$$

- (2) The linear combination of L weight vectors is

$$u = \sum_{k=1}^L \alpha_k u_k^T, \quad (B.13)$$

where $\alpha = \{\alpha_1, \alpha_2, \dots, \alpha_L\}$ is the linear combination coefficient. $\{u|u = \sum_{k=1}^L \alpha_k u_k, \alpha_k > 0\}$ is the set of possible weights.

- (3) In order to select the most satisfactory weight in u , the linear combination coefficient α_k of should be optimized to minimize the difference value between u and u_k . The objective function is

$$\min \left\| \sum_{k=1}^n \alpha_k u_k^T - u_k^T \right\|, k = 1, 2, \dots, L. \quad (B.14)$$

- (4) The optimal first derivative condition is

$$\sum_{j=1}^L \alpha_j u_j u_j^T = u_i u_i^T \quad (i = 1, 2, \dots, L). \quad (B.15)$$

- (5) The optimized combination coefficient $(\alpha_1, \alpha_2, \dots, \alpha_L)$ is normalized to obtain $\alpha^* = \alpha_k / \sum_{k=1}^L \alpha_k$. Finally, the fusion weight u^* is obtained, namely,

$$u^* = \sum_{k=1}^L \alpha_k^* u_k^T, k = 1, 2, \dots, L. \quad (B.16)$$

B.3. Comprehensive Utility Ranking Based on the CW-VIKOR Method

- (1) Determine the positive ideal solution P^* and negative ideal solution P^- of each index.

$$P^* = \{y^*\} = \max_{i=1}^n (y_{ij}),$$

$$P^- = \{y^-\} = \min_{i=1}^n (y_{ij})$$
(B.17)

where y_{ij} is the normalized value of the index.

- (2) The group benefit value S_i and the maximum individual regret value R_i are calculated.

$$S_i = \sum_{j=1}^m \omega_j \frac{(y_j^* - y_{ij})}{(y_j^* - y_j^-)},$$

$$R_i = \max_j \omega_j \frac{(y_j^* - y_{ij})}{(y_j^* - y_j^-)}$$
(B.18)

where ω_j is the fusion weight determined by the game theory. The smaller S_i is, the higher the group benefit of regional water resource life cycle utility is. The smaller R_i is, the smaller individual regret of regional water resource life cycle utility is.

- (3) The comprehensive utility value of water resource life cycle sustainability is calculated

$$Q_i = \nu \frac{S_i - S^-}{S^* - S^-} + (1 - \nu) \frac{R_i - R^-}{R^* - R^-},$$

$$S^* = \max_i \{S_i\}, S^- = \min_i \{S_i\}; R^* = \max_i \{R_i\}, R^- = \min_i \{R_i\}.$$
(B.19)

ν is the utility decision coefficient, which is used to measure the subjective preference of decision makers. If $\nu > 0.5$, the decision of the overall optimal utility is preferred. If $\nu < 0.5$, the decision that pays more attention to minimum individual regret value is preferred. In this paper, $\nu = 0.5$ is selected to evaluate the utility of water resources life cycle in a half-measure way. The smaller the Q_i value is, the higher the comprehensive utility value of water resource life cycle sustainability is.

- (4) Sort according to the values of Q_i , S_i , and R_i . The smallest value is the best value of utility.

Data Availability

All data are presented in the article and appendices.

Conflicts of Interest

The authors declare no conflict of interest.

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