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Allocation and Utilization of Coal Mine Water for Ecological Protection of Lakes in Semi-Arid Area of China

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Abstract: In the background of water ecological protection, how to utilize the superfluous coal mine water efficiently has become an urgent problem, especially in northwest China, where the fragile ecological environment needs to be protected but lacks water. To solve this problem, this study proposes a new procedure for the allocation and utilization of mine water aimed at the ecological protection of lakes in an arid and semi-arid area. Based on the water balance method, the ecological water supplement of regional lakes is first estimated according to their different protection goals. Next, a trend analysis of water demand and supply is carried out, and the mine water inflow and available quantity are calculated. Meanwhile, the water resource allocation plan is evaluated systematically. In this study, the procedure is applied to the mine water and lakes in Wushen Banner, Inner Mongolia Autonomous Region of China. The results show that: (1) the lakes can be divided into three classifications according to their ecological protection goals, (2) the available amount of mine water will reach 57.17–81.97 million m^3 in 2030, and there are about 46.7 million m^3 of water that can be adjusted to reach the optimal utilization in 2020, and (3) the mine water after advanced treatment could meet the requirement of lakes. Finally, it outputs the water supplement path and the water quantity, as well as the water transmission pipelines to each lake, which makes up a new water resources allocation plan and a utilization mode of regional mine water. This utilization mode can provide solutions and ideas for improving the ecological environment of regional lakes and promote the construction of regional ecological safety barriers. Moreover, it can be very helpful for optimizing the allocation of regional water resources, and for improving the reasonable utilization of coal mine water.

Keywords: mine water; ecological conservation; efficient utilization of water resources; allocation of water resources

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1. Introduction

Northwest China is rich in coal resources but poor in surface water resources. With the exploitation of coal mines, a large amount of groundwater is released. If this amount of groundwater is not reasonably utilized, it will not only lead to environmental pollution [1] or ecological accidents [2], but also waste valuable water resources. Meanwhile, the water ecosystem is very sensitive to the water. With the recent intense human activities and climate change, the ecological functions are seriously degraded, especially for lakes in plateau and desert hinterlands. There needs to be a stable water source and reliable water supply and water quality to improve the ecological environment and its functions.

Many researchers have studied the utilization mode of mine water [3–6]. It can be transformed into an underground reservoir [7,8], used as a reserve water source, used for the production water of surrounding enterprises [9,10], underground power generation, and vegetation irrigation water [11], and it can also be put into the urban pipeline network after advanced treatment [12]. In recent years, a series of policies have been issued in China to ensure that unconventional water sources, such as mine water and recycled water, are fully and efficiently used. For example, in 2019, the "National Water Conservation Action Plan" required that the utilization of unconventional water including mine water in water-scarce areas should be strengthened [13]. In cities with abundant mine water resources, it is also necessary to make full use of mine water resources in their local development plans and circular economy development plans. Due to the different quantity and quality of coal mine water and the significant differences in regional conventional water resources conditions, the comprehensive utilization and optimal allocation mode of mine water needs to be considered based on actual conditions. However, there is no typical practice of bringing mine water into the unified allocation of regional water resources.

According to the European Environment Agency (EEA), the prevention of water pollution and the scientific allocation and management of water resources are important to the utilization of freshwater resources, and it is necessary to protect and restore the water ecosystem of rivers, lakes, and reservoirs [14,15]. Lakes in arid and semi-arid areas of China are very sensitive to regional climate change and human activities. They are not only indicators of climate change, but also an important part of the regional water cycle [16]. Lakes are a unique part of the plateau landscape in northwest China, and it has important ecological functions [17], such as a transfer station for migratory birds, climate regulations, and prevention of wind and sand erosion [18]. For example, due to the intense human activities and continuous warming and less rain, bird habitats around the world are facing the threat of degradation [19]. Similarly, in the Ordos Plateau of China, the important breeding habitat of *Relict gulls* was shrinking rapidly, and the wetlands in the region were seriously degraded in the 1990s, so the breeding number of *Relict gulls* fluctuates sharply [20]. In the desert hinterland of Ordos Plateau, maintaining a certain lake surface area can prevent sand erosion and alkali from blowing up with the wind. Regarding the protection of ecological functions of the lake, China has promulgated clear laws and regulations to strengthen lake management and protection, improve lakes' ecological environment, maintain the ecological health of lakes, and realize sustainable utilization of lakes' functions.

In arid and semi-arid areas, on the one hand, water resources are extremely scarce, but the ecological protection of plateau lakes requires stable and continuous water sources. On the other hand, the surplus of mine water needs to find a way out, thus to solve the disorder discharge and environmental pollution problems. The dual questions need to be solved simultaneously. Taking the Wushen Banner of Ordos, Inner Mongolia, China, as an example, by calculating the amount of ecological water supplement of plateau lakes in urgent need of protection, reviewing the regional water resources allocation plan and the available amount of mine water in the whole banner, combined with the existing water system connection network and mine water transmission and distribution pipeline network, this paper proposes a new water resources allocation plan based on water ecological protection of local lakes. This new mode could provide solutions and ideas for the overall solution of the old problems of ecological water shortage in the inner flow area (rivers flow to the lowest point in the area without out-flowing) and the new questions of surplus of mine water in the outflow area, and also for the optimal allocation of Wushen Banner's water resources.

2. Methodology and Materials

2.1. Study Area

Wushen Banner is located in the southwest of Ordos City, Inner Mongolia Autonomous Region of China (See Figure 1). It is also in the hinterland of the Mu Us Sandy Land and the arid and semi-arid temperate continental climate zone. The annual average ground surface temperature from 1958 to 2019 is 10.2 °C [21], while the annual average precipitation is 351.4 mm, and the precipitation is mainly concentrated in the months of June to September [22]. The annual average potential evaporation is 1387 mm. The altitude decreases from the west and north to the east and south, the high areas are eroded land and the low areas have inland alkalized lakes. In the middle and south areas, there are alternating ridges and beaches.

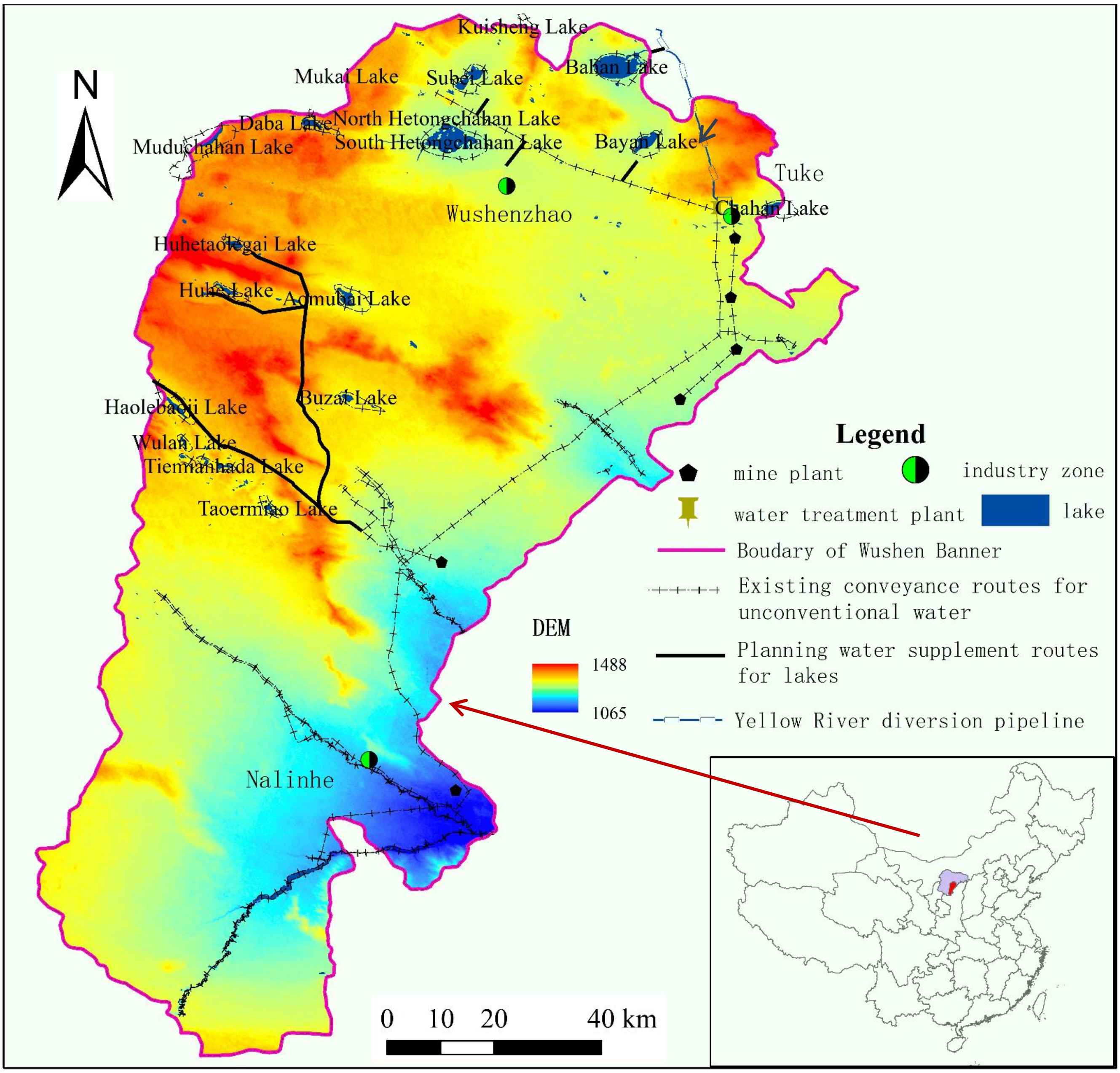

Figure 1. Study area.

The water system of Wushen Banner is divided into the inner flow area and the outflow area. The northern part belongs to the inner flow area of the Ordos Plateau, and a little surface runoff forms various sizes of inland lakes and wetlands; while the southern part belongs to the Wuding River Basin, a first-level tributary of the Yellow River [23]. There are 32 small lakes in Wushen Banner, mainly distributed in the north of the inner flow area, and the water resources are inherently insufficient relative to water demand. There are about 21 lakes with water all year round, and the total water surface area is about 90 km^2. The largest lake is Hetongchahan Lake, followed by Bahan Lake, and the respective water surface area of the two lakes is more than 10 km^2.

Since the 1980s, lake areas have shrunk drastically, their ecological functions have been destroyed [24], the number of birds has dropped sharply, and the function of Aomubai

Lake as the concentrated breeding habitat for *Relict gulls* has disappeared. The remote sensing image data from 1988 to 2018 of 13 lakes in Wushen Banner shows that there was a significant shrinking period of lake area around the year 2000 [25]. Fortunately, after Wushen Banner's vigorous promotion of the construction of ecological civilization, some lakes showed signs of improvement. Under the current situation, it lacks stable and continuous water sources that meet the quality and quantity requirements.

Wushen Banner is rich in coal, and the suitable mining area is more than 4000 km^2. There are two major mining areas in Wushen Banner: Hujierte Mining Area and Nalin River Mining Area, both belonging to the Dongsheng coal field. As of the end of 2019, six mines in the whole banner have been put into production, and three more mines will be put into operation by 2030. They are all underground mines, and with the continuous development of roadway excavation, the amount of coal mine water (ground water) is increasing.

With the implementation of the most stringent water resources management laws, the effect of water saving throughout Wushen Banner has gradually emerged, while the water consumption has been relatively stable. Therefore, a new situation of surplus mine water in the outflow area and idle water resources delivered from the Yellow River has appeared.

2.2. Methodology

To solve the practical problem of bringing mine water into the unified and allocation of regional water resources, and also to solve the problem of lake function maintaining, it is necessary to comprehensively consider the supply and demand conditions and the potentiality of regional water resources, the present and the future economic development level, and project layout. To set up the reasonable utilization mode of mine water to protect the lakes of Wushen Banner, the technical route contains five procedures in this paper.

Firstly, three main aspects of the current situations are assessed, including calculating the lakes' ecological water supplement; reviewing the regional water resources allocation plan according to the situation of current water supply (especially mine water) and its utilization; and calculating the mine water inflow and available quantity, and analyzing the water quality and quantity requirement of mine water for lake water ecological protection. Secondly, regional water resources supply and demand is analyzed, and the allocation plan of water resources including mine water is determined. Finally, using the existing water pipes, a new water supply routes for lakes' water demand is designed. Thus the efficient utilization mode of mine water for lakes is proposed (see Figure 2). Figure 3 gives a more detailed idea and calculation methods.

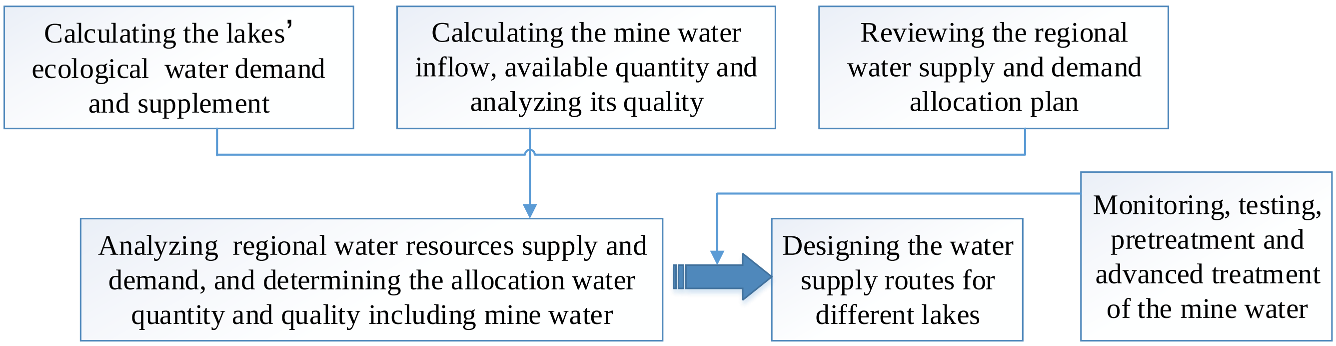

Figure 2. Processes of the utilization mode of mine water aimed for ecological protection of lakes.

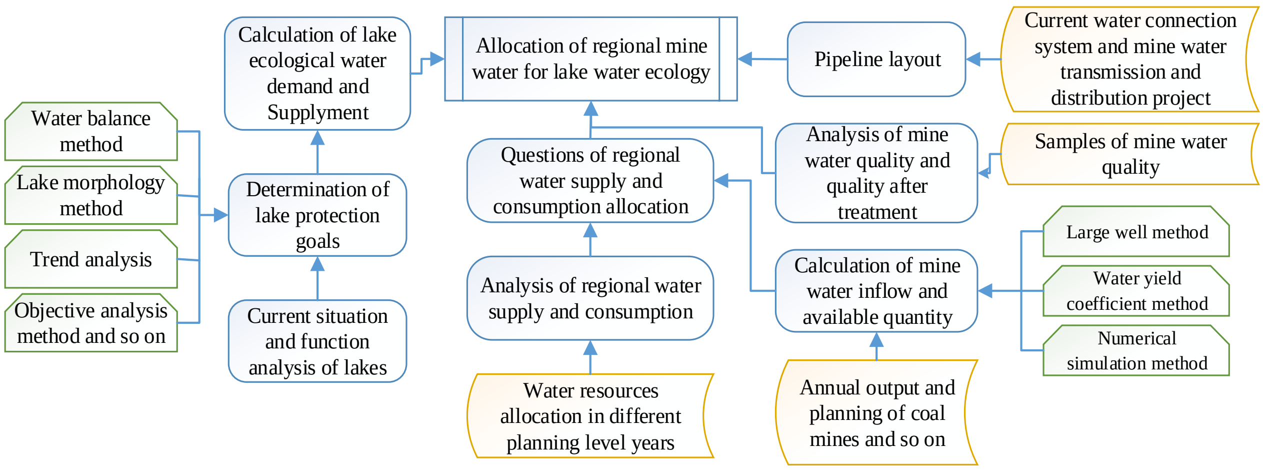

Figure 3. Detailed idea and methods of the main processes.

2.2.1. Calculation Method of Lake Ecological Water Demand and Supplement

There are many methods to calculate a lake's ecological water demand and supplement, such as the minimum water level of the lake [26], the method based on the aquatic ecosystem, wetland, and vegetation [27], the water balance method, and the lake functions method. In this study, the ecological water supplement is calculated by the water balance method [15], according to the different protecting goals and the basic water area of the lakes to maintain.

Considering the ecological function of each lake, based on the current ecological and environmental conditions, combined with the development and utilization mode of the lakes, the ecological protection goal of each lake is determined comprehensively. The detailed analysis of important lakes' ecological functions is shown below. Then, the basic water surface area of each lake that needs to be maintained is obtained through the lake morphology method, trend analysis method, and basic ecological water area method.

We calculate the water surface evaporation as the evaporative losses for the lakes. The lakes are the lowest points of the basin, so we do not consider the leakage. We also do not consider the precipitation measurement/changes over time due to climate change. Since the calculation of water balance of regional lakes is a complex process and high-skilled work, it is discussed more detail in the literature [25] and will not be repeated here.

2.2.2. Analysis Method of Regional Water Resources Supply and Demand

In the future, water-saving efforts will be further strengthened. In particular, newer and higher requirements for water-saving were proposed at the symposium on ecological protection and high-quality development of the Yellow River Basin on 18 September 2019 [28]. Therefore, it is generally regarded that the annual water consumption of Wushen Banner will remain relatively stable in the future, but the water use structure will undergo profound changes. Compared with the current situation, the domestic water will have little change. The water supply source will be groundwater, so the supply reliability will be high and the water source will be stable. The agricultural water will decrease year by year, and the main water supply sources will be surface water, and some recycled water or groundwater. The water source is relatively stable, and the change will be small compared with the current situation in the future. In light of the above, we focus on the change of water supply and demand in industry and ecological environment. We use the simple linear regression model to analyze the industrial water consumption trend:

$$Y = ax + b \tag{1}$$

where Y is the estimated industrial water consumption per year, m^3; a is the growth trend of the industrial water consumption; and b is the constant of the equation.

2.2.3. Calculation Method of Mine Water Inflow and Available Quantity

With the exploitation of coalfields, much water will be extracted from the underground aquifer. To calculate mine water inflow, virtual large diameter well method [29], rich water coefficient method, numerical simulation [30], and the global optimization-based method [31] are commonly used. In this paper, the water inflow of mine plants in the future is calculated by the mine water coefficient method [32]. The formula is as follows:

$$Q = K_p \times P \quad (2)$$

where Q is the estimated water inflow of coal mines, m^3/a; Kp is the water yield coefficient of mining per ton of coal in one year, m^3/t; and P is the design output of the coal mines, t/a.

The treatment loss for mine water of the advanced treatment plant is set to 15%, and after subtracting the water consumption of the mine plants (obtained from investigation of the 6 mine plants of Wushen Banner in 2019, the water is used in the underground grouting, road watering, and vegetation irrigating), the available quantity of mine water is obtained.

2.3. Data Collection

Aside from the lake water demand and supplement calculation, a lot of data need to be collected to analyze the regional water demand and supply in the future, then to get the reasonable allocation of the regional water resources. The data used and collected in this paper are described as follows.

2.3.1. Regional Water Resources Utilization Data

The Wushen Banner Water Resources Bulletin data from 2010 to 2019 are used to analyze the water supply and demand of regional water resources. The future regional water use data in 2025 and 2030 come from the "Water system connectivity and industrial water supply guarantee plan of Wushen Banner" [33] and the "Mine water utilization scheme of Wushen Banner" [34], which are approved by the government of Wushen Banner. The quantity of water supply and its composition each year are shown in Table 1.

Table 1. Water supply of Wushen Banner from 2010 to 2019. Unit: 10^4 m^3.

Year	Ground Water	Water from Yellow River	Surface Water	Recycled Water	Mine Water	RAINFALL	Total
2010	17,430		8376				25,806
2011	17,842		8376				26,218
2012	16,024		8376				24,400
2013	19,102		4272	92			23,466
2015	19,866		2630		760		23,256
2017	16,224	1113	5309	481	1892		25,019
2018	17,396	1125	3782	308	1908	60	24,579
2019	18,103	40	3201	315	3442	0	25,101

2.3.2. Regional Water Resources Allocation in Different Planning Level Years

These data are collected to compare and analyze whether the allocation of the water resources in the future is reasonable, and to bring forward the reasonable allocation plan according to the current situation.

According to the approved "Water system connection and industrial water supply guarantee plan of Wushen Banner" and the "Mine water utilization scheme of Wushen Banner" mentioned above, the total water demand in 2025 is 309 million m^3, of which 4.83 million m^3 is domestic water demand and 138.13 million m^3 is industrial water demand. The eco-environmental water demand outside rivers is 5 million m^3. The total water demand in 2030 is 339 million m^3, of which the domestic water demand is 5.15 million m^3, the industrial water demand is 170.90 million m^3, and the eco-environmental water demand outside rivers is 5.11 million m^3. Table 2 lists the forecasted amount of water demand in the year 2025 and 2030. We can see that the industry water demand has more difference in the year 2025 and 2030 (See the Figure A1 for details).

Table 2. Forecasted amount of water demand in different years in Wushen Banner. Unit: 10^4 m^3.

Different Planning Level Year	Domestic Water Consumption	Industry	Construction Industry and Tertiary Industry	Agriculture and Animal Husbandry	Livestock	Ecological Environment Water Demand outside Rivers	Total
2025	483	13,813	258	14,559	1332	500	30,944
2030	515	17,090	252	14,210	1339	511	33,917

At the same time, in the year 2025, through the construction of a number of surface water intake projects, as well as the Nalin River branch line, the pipeline connecting the Batuwan Reservoir to the Nalin River Water Treatment Plant, and the Yellow River Diversion Main Line, the water system connection pattern of Wushen Banner will be initially formed. Table 3 lists the forecasted amount of water demand and supply in the year 2025 and 2030.

Table 3. Forecasted amount of water demand and supply in different years in Wushen Banner. Unit: 10^4 m^3.

Different Planning Level Year	Water Demand		Water Supply			
	Total Water Demand	Industry	Surface Water	Underground Water	Mine Water	Total Water Supply
2025	30,944	13,813	10,727	16,054	3674	30,455
2030	33,917	17,090	12,058	15,867	4913	32,838

2.3.3. Mine Water Data

1. The actual monitoring data of mine output, mine water inflow, and the usage of 6 coal mines in 2018 and 2019 are used to analyze the changing characteristics of mine water inflow and the available quantity in the future.

As of the end of the year 2019, Wushen Banner has 6 coal mine enterprises (see Table 4). The designed output of the 6 coal mines is 61 million tons per year. With reference to the "Thirteenth Five-Year Plan for Coal in Wushen Banner", "General Plan for Hujierte Mining Area", and "General Plan for Nalin River Mining Area", another 3 coal mines will be put into operation from 2020 to 2030, and the annual output of coal will be 85 million tons. The available amount of mine water for each enterprise of coal mine in 2019 is shown in Table 4.

Table 4. Available amount of mine water of coal mining enterprises of Wushen Banner in 2019. Unit: 10^4 m^3.

Coal Mining Enterprises	Discharge	Water Consumption	Water Treatment	Treatment Loss	Available Amount
No.2 Nalin River Mine	849.17	70	779.17	116.88	662.30
Muducaideng Mine	1175.14	49	1126.14	168.92	957.22
Menkeqing Mine	895.00	158	737.00	110.55	626.45
Hulusu Mine	744.41	75	669.41	100.41	569.00
Bayangaoleng Mine	464.59	250	214.59	32.19	182.40
Yingpanhao Mine	803.00	125	678.00	101.70	576.30
Total	4931.31	727	4204.31	630.65	3573.66

According to the forecasted results of the "Mine water utilization scheme of Wushen Banner" [34], among the unconventional water sources, the amount of available mine water in Hujierte and Nalin River Mining Areas is as follows: in the year 2025, the amount will be 25.98 million m^3 with the total annual coal mining 61 million tons; while in the year 2030, the amount will be 31.94 million m^3 with the total annual coal mining 85 million tons.

2. The water quality samples are collected to analyze the mine water quality and quality after treatment, such as water inflow quality samples after advanced treatment of Bayangaole Mine in August 2019 and March 2020, and that of Menkeqing Mine in November 2019 and March 2020; as well as the water inflow quality samples of No.2 Nalin Mine from August to December 2019 (6 times of samples), and the water inflow quality

samples and advanced treatment samples of Yingpanhao Mine in November 2019 and April 2020. See the literature [35] for details.

2.3.4. Water Resources Bulletin Data of Other Regions and Yellow River Water Utilization Data

The National Water Resources Bulletin, Inner Mongolia Water Resources Bulletin, Ordos Water Resources Bulletin from 2010 to 2018 are collected to compare and analyze the trend of water use in Wushen Banner in the future.

According to the water allocation plan of the Yellow River Basin, there are 27.29 million m^3 of water from the Yellow River that Wushen Banner can use. The amount of Yellow River water used in 2017, 2018, and 2019 is 11.13 million m^3, 11.245 million m^3, and 0.4 million m^3, respectively.

3. Results

3.1. Results of Lake Ecological Water Supplement

3.1.1. Ecological Protection Goals of Lakes

(1) Function of birds' habitat

Some lakes and wetlands in Wushen Banner are the transfer station and breeding habitat for the first-class protected animals, such as the *Relict gull*, as well as the second-class protected animals, such as the swan, the green winged duck, the wild goose, the red duck, and the mallard. One of the most important ecological protection goals of the lakes is to be protected as the birds' habitat.

(2) Function of ecological balance maintain

Wushen Banner is located in the semi-arid area of China, which belongs to the area of wind prevention and sand fixation in the national ecological function zone. When a lake and its surrounding wetland vegetation act as the sandy oasis, it has an important ecological function of wind prevention, sand erosion control, and climate regulation. Due to the common influence of climate change and human activities, nearly two-thirds of sandy lakes have dried up to some degree. When the lake dries up, the vegetation around the lake disappears due to the lack of groundwater support, and the exposed beach becomes the source of wind and sand. Therefore, maintaining a certain area of water surface and preventing beach desertification is one of the important ecological protection goals.

(3) Stopping the exploitation of alkali and restoring the ecosystem in an all-round way

According to the field investigation and data analysis, most of the lakes in Wushen Banner are alkali lakes, which have been exploited for more than 100 years. At present, the alkali resources have been exhausted. Because there is no dynamic supplement, the amount of thermonatrite resources is also decreasing. Moreover, the exploitation of alkali lakes has a great impact on the lake ecosystem, such as disorderly mining, low degree of comprehensive utilization, and excessive exploitation of brine resources. At present, the topography and geomorphological characteristics of alkali lake area are seriously damaged, and the lake area is no longer in the shape of a natural lake. A large number of mining wastes are accumulated in the lake area. Thus, except for the Muduchahan Lake, the exploitation of alkali needs to be stopped and the ecological environment of lakes needs to be fully restored.

According to the protection goal analysis above, the classification of protection goals of some important lakes in the region is shown in Table 5, and the location of these lakes can be seen in Figure 1.

Table 5. Classification of some important lakes and their protection goals in Wushen Banner.

Protection Goals	Functions of the Lake	Lakes of Classification
Transfer station and breeding habitat	Transfer station and breeding habitat for some protected birds and animals	Bayan Lake, Aomubai Lake, Hetongchahan Lake, Hamarigetai Lake, Huhetaolegai Lake, Haolebaoji Lake, Guribanwulan Lake, Chaganzhadagai Lake
To maintain a certain area of water surface	To maintain ecological balance, wind prevention and sand control and climate regulation, and acting as the ecological barrier	Bahan Lake, Muken Lake, Buzai Lake, Wulan Lake, Eruhe Lake, Tiemianhada Lake, Daba Lake, Barisonggu Lake
To stop the exploitation of alkali and to restore the ecosystem	To maintain the shape of natural lake	Muduchahan Lake, Chahan Lake, Huhe Lkae, Subei Lake, South area of the Hetongchahan Lake

3.1.2. Basic Water Surface Area of Important Lakes

The minimum water surface area of a lake is determined based on its ecological protection goals.

The basic water surface area of Bahan Lake is calculated according to the lake morphology method using GIS software. As to the lake capacity curve, when the area is 13 km^2, there is a mutation point, which means that it is the largest possible water surface area by using the same amount of water. When there is some water in the small lake in the south of Bayan Lake, we think that it has the minimum basic ecological water surface area. According to the comparison of historical images and combined with the normal water surface area data of the General Survey of Water Resources, the basic ecological water area of Bayan Lake is determined as 3.68 km^2.

As to the protection goals of bird breeding habitat of Aomubai Lake, the recorded area of 5 km^2 in 1991, when there were the most birds, is regarded as the basic ecological area. The north of Hetongchahan Lake also takes the protection of bird habitat as the goal, and the basic water surface area is 6 km^2; while the south of Hetongchahan Lake aims at repairing the alkali mining area of the lake. According to the General Survey of Water Resources, the annual water area is 20 km^2. Subtracting the 6 km^2 of ecological protection area in North Lake area, 14 km^2 is left for the South Lake.

According to the historical change trend of the surface area of Subei Lake, the value reaching 2/3 of the water surface area is 4.07 km^2. According to the General Survey of Water Resources data, the annual water surface area is 4.1 km^2, so the basic water surface area of Subei Lake is determined as 4.1 km^2 comprehensively.

Other lakes: in the water quality tests this time, the mineralization degree of Hamarigetai Lake is 6.16 g/L and that of Haolebaoji Lake is 11.5 g/L, which both belong to saltwater lakes. The ecological protection goals are to protect aquatic organisms and birds' breeding habitats. Considering the salt tolerance limit of 6 g/L of aquatic organisms and combining the present mineralization degree of the two lakes, the basic surface water area of Hamarigetai Lake is determined when the salinity is 5 g/L, while when the salinity is 8 g/L, the corresponding lake area can be seen as Haolebaoji Lake's basic water surface area. Then, the corresponding basic water surface area of the two lakes is 0.2 km^2 and 5.5 km^2, respectively.

According to the results above, with the condition of average water quantity, when the basic ecological water surface area is reached, the total area of lakes in Wushen Banner is 69 km^2.

3.1.3. Ecological Water Supplement of Important Lakes

Considering the water balance of lakes, combined with regional hydrological and geological conditions, to maintain the minimum water area of the lakes, the total water supplement of lakes for ecological goals is 18.42 million m^3 per year, and the main lakes in need of supplement are Bahan Lake, Bayan Lake, Subei Lake, Kuisheng Lake, Hetongchahan Lake, Muken Lake, Aomubai Lake, and Haolebaoji Lake. The ecological water supplement for lakes can be seen in Table 6.

Table 6. Ecological water supplement for lakes in Wushen Banner.

Name of the Lake or Lakes	Water Quantity of Supplement/Million m^3	Name of the Lake or Lakes	Water Quantity of Supplement/Million m^3
Bahan Lake	5.83	Bayan Lake	0.923
Subei Lake, Sand Kuisheng Lake	1.113	Hetongchahan Lake, Muken Lake, and small lakes surrounding	8.178
Aomubai Lake and small lakes surrounding	0.634	Haolebaoji Lake	1.738

3.2. Trend Analysis Results of Water Demand and Supply of Wushen Banner

3.2.1. Water Sources Analysis

From the analysis of regional water resources utilization data, water sources for agriculture are local surface water and groundwater; all rural and urban domestic water comes from groundwater. Urban environment and rural ecological water almost all come from groundwater and only a small amount of rainwater or recycled water began to be used from 2018, while industries make full use of groundwater, water from the Yellow River, local surface water, recycled water and mine water.

Before the year 2012, Wushen Banner only used the water from the conventional water source, and with the rapid development of the regional economy, recycled water began to be used from the year 2013. As the coal mines are put into operation, the coal mine enterprises' mine water is included in the regional water resources allocation from the year 2015. Subsequently, the Yellow River diversion water is used from the year 2017.

Since the implementation of the stringent water resources management laws from 2012, the annual total water consumption in Wushen Banner has been stable. The water consumption in 2018 was 16.39 million m^3 less than that in 2011, and that in 2019 was 11.17 million m^3 less than that in 2011. Thus, we can see that the water supply and demand in industry and ecological environment are most likely to change in the future, and they are mainly analyzed as follows.

3.2.2. Industrial Water Supply and Demand

On the basis of regional water resources allocation data in the year 2020, 2025, and 2030, the planned industrial water demand in 2020 was 89.14 million m^3 (including 87.66 million m^3 of water demand in industrial zones). However, the actual industrial water consumption in 2018 and 2019 were 52.27 million m^3 and 50.72 million m^3, respectively. The consumption in 2020 is more or less the same as that in 2019. Therefore, the industrial water consumption in 2020 is about 39 million m^3 less than the predicted water demand.

The trend of industrial water consumption is shown in Figure 4 (the unit of industrial water consumption of China is 100 million m^3, and the rest of that is million m^3). Y_e and Y_w in Figure 4 represent the linear regression equations of Ordos city and Wushen Banner, respectively.

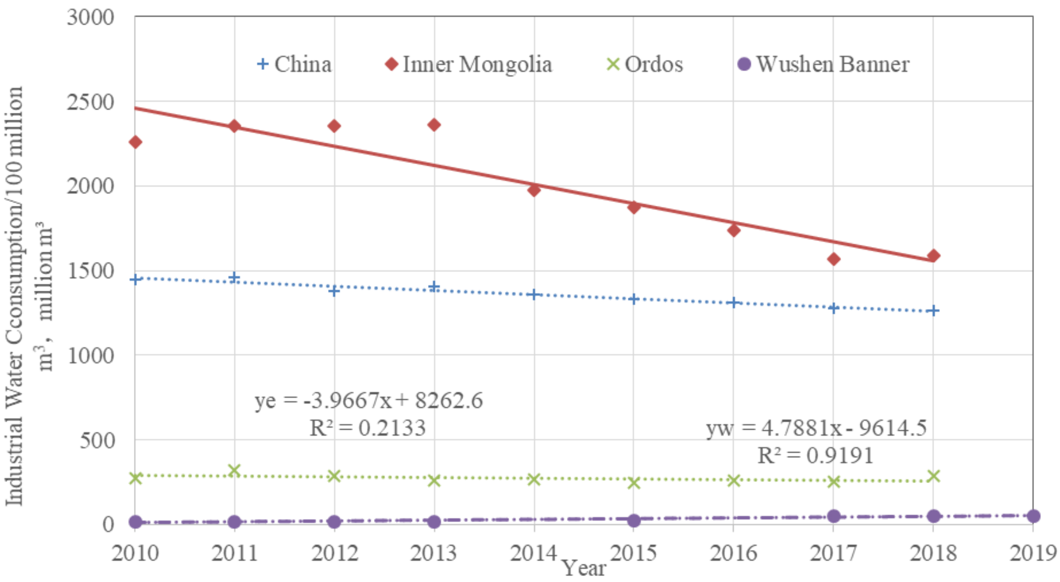

Figure 4. Trend of industrial water consumption of China, Inner Mongolia, Ordos, and Wushen Banner.

From Figure 4, it is obvious that the industrial water consumption of China, Inner Mongolia, and Ordos show a downward trend, especially in Inner Mongolia, but that of Wushen Banner shows a slight increase. With the implementation of the "National water saving action plan" and the "Water saving action implementation plan of Inner Mongolia Autonomous Region", Wushen Banner will adjust the industrial structure and spatial layout further, and implement industrial water saving and emission reduction actions, then the possibility of a continuous and substantial increase of industrial water consumption will be reduced. Even according to this increasing trend, the industrial water consumption in 2025 and 2030 will be 81.40 million m^3 and 105.34 million m^3, respectively, using the linear regression equations of Y_w, which will still be far less than the predicted water demand of 138.13 million m^3 in 2025 and 170.9 million m^3 in 2030.

3.2.3. Ecological Water Supply and Demand

By the current situation of ecological water supply and consumption in the whole banner, urban and rural ecological environment is the biggest water consumer, and the water source is mainly groundwater. Only a small amount of rainwater was used in 2018. According to "Water system connection and industrial water supply guarantee plan of Wushen Banner", the ecological water demand of important lakes in the region was not considered. In order to maintain the basic water surface area of the important lakes, it needs about 18.42 million m^3 of water. Therefore, it is necessary to find suitable water supply sources and sufficient water quantity, and also to ensure certain water quality.

3.3. Mine Water Inflow and Available Quantity

3.3.1. Actual Utilization of Mine Water

From Tables 1 and 4, the actual amount of mine water inflow is more than that of water supply. In the year 2019, the actual amount of mine water inflow reached 49.31 million m^3, and the available amount of coal mine water reached 35.74 million m^3 (refer to the last row in Table 4), but the actual water supply was 34.42 million m^3 (refer to the last row in Table 1), and the unused amount was 1.32 million m^3. The actual available amount in 2019 exceeded the predicted water supply of 29.56 million m^3 in 2020 and that of 31.94 million m^3 in 2030. This means the mine water is not effectively utilized.

3.3.2. Water Inflow of Coal Mines

Compared with the predicted inflow [34], the actual amount of mine water inflow in 2019 (49.31 million m^3) exceeded the predicted inflow of 44.27 million m^3 in 2020, and is very close to the predicted amount of 50.25 million m^3 in 2030. In other words, the water inflow of the coal mine enterprises is larger than the predicted value.

As to the actual investigation of mine water in 2019, the current inflow amount of coal mine enterprises was 49.31 million m^3. According to the work report of the government of Wushen Banner in 2019, the coal output in 2019 was 40.36 million tons. Thus, the water yield coefficient of mining per ton of coal in one year K_p is 1.22 m^3/t. Using the mine water coefficient method mentioned above, in the ideal state in this paper, the mine water inflow of the 6 coal mining enterprises in Wushen Banner in 2030 is estimated about 74.53 million m^3, with the total output of coal 61 million tons; and it may be 103.7 million m^3 in 2030 with the total output of coal 85 million tons of 9 coal mining enterprises.

3.3.3. Available Quantity of Mine Water in the Future

According to Section 2.2.3., when the total amount of coal mine inflow reaches 74.53 million m^3 in 2030, the available amount of mine water will reach 57.17 million m^3. In the same way, the available amount of mine water will reach 81.97 million m^3 in 2030 while the output of the coal reaching 85 million tons. According to relevant policies, this part of water should be included in the regional allocation of water resources, which can be used for industrial, ecological environment, and urban miscellaneous items.

3.4. Results of Mine Water Quality and Quality after Treatment

In view of the preliminary analysis of 12 water quality samples collected from 6 lakes, Bahan Lake, Bayan Lake, Hetongchahan Lake, Hamarigetai Lake, Aomubai Lake, and Haolebaoji Lake, from 19 to 20 December 2019, the pH, conductivity, salinity, permanganate, chemical oxygen demand, ammonia nitrogen, total phosphorus, total nitrogen, fluoride, sulfate, chloride, and fecal coliform were tested [35]. The results show that the ammonia nitrogen in the lakes is low, reaching the class III–IV standard of surface water [36], and the fecal coliform in all lakes is also low. However, the other indicators are generally high. The salinity of the water is high, except Hamarigetai Lake and Haolebaoji Lake, whose salinities are lower than 35 g/L.

According to the collected water quality data, there are two indicators in Bayangaole Mine's water quality in August 2019 that exceed the class III standard of surface water, and the testing indexes in March 2020 could meet the class III standard. The quality of water inflow and advanced treatment water of Yingpanhao Mine and the quality of advanced treatment water of Menkeqing Mine could meet the class III standard of surface water; meanwhile, the water quality after advanced treatment is better than that of raw water. Due to the lack of surface water testing index, the mine water quality of No.2 Nalin Mine needs further testing. The results can be seen in Table 7.

Table 7. Water quality testing results of the collected samples.

Name of Coal Mines	Date of Water Samples	Raw Mine Water	Mine Water after Treatment
Bayangaole	August, 2019	-	Two indicators exceed the class III standard of surface water.
	March, 2020	-	All indicators meet the class III standard.
Yingpanhao	November, 2019 and April, 2020	All indicators meet the class III standard.	All indicators meet the class III standard.
Menkeqing Mine	November, 2019 and March, 2020	-	All indicators meet the class III standard.
No.2 Nalin Mine	August to December, 2019 (6 times of samples)	Need further testing.	-

3.5. Reasonable Allocation and Utilization Mode of Mine Water

The surface water, groundwater, and Yellow River water as the industrial water supply sources will have little change overall when the regional climate and policy are unchanged. The recycled water may be reduced compared with the planned value due to the decrease in the number and scale of industrial enterprises. Moreover, the amount of recycled water is less than other water sources and mine water, so the reduction can be ignored. In summary, compared with the predicted value in 2020, the actual industrial water demand is about 39 million m^3 lower than the planned value, and the mine water supply is about 7.7 million m^3 higher than the planned value (29.56 million m^3). Therefore, under the condition that the water consumption of other water users has little change, there are about 46.7 million m^3 of water resources that can be optimized and adjusted. Thus, it is urgent to integrate the mine water into the regional unified allocation to find a reasonable and efficient utilization way. Meanwhile, the treatment of the mine water needs to be conducted prior to release into lakes and rivers. According to the analysis of the water quality of mine water after advanced treatment, the water quality could meet the requirements of the lakes.

With the average value for many years, it is necessary to supply about 18.42 million m^3 of water per year to maintain the basic water surface area of the important lakes in Wushen Banner. According to the actual investigation of the coal mine locations and the available water supply of the mine water in the year 2018 and 2019, priority should be given to the allocation of mine water for the lakes. Therefore, the water supplement path and the water quantity for each lake are proposed, as seen in Figure 5. It is the allocation plan for the lakes and also for the regional water demand and supply in the next few years.

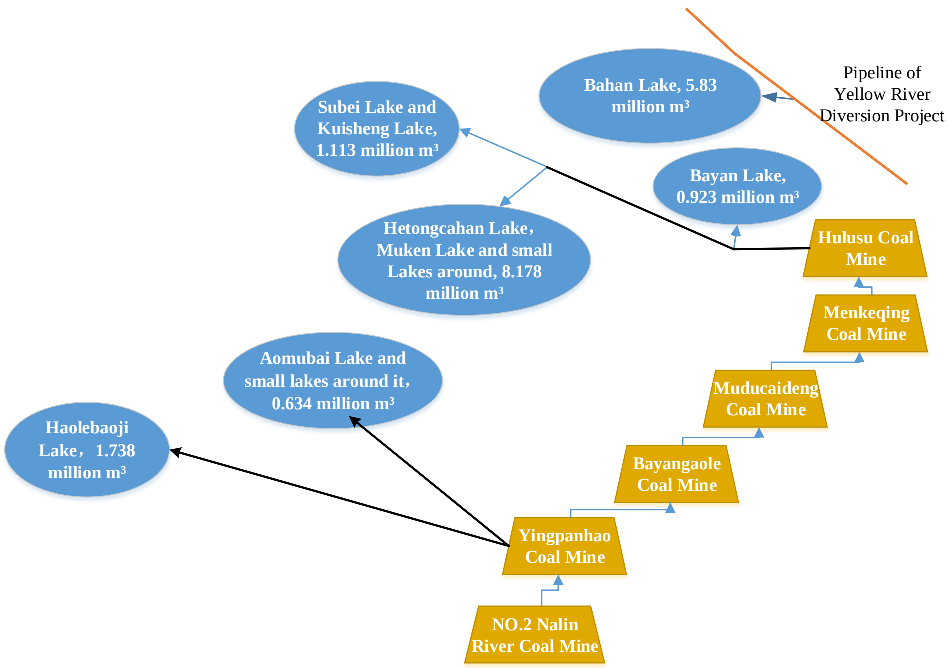

Figure 5. General idea of water supplement path and the water quantity supplied to the main lakes in Wushen Banner.

Using GIS software, based on the DEM and proximity, the pipelines of ecological water supply and transmission project aimed at the important lakes are arranged. It also considers making full use of existing pipelines and reasonable project scale. Six main water transmission pipelines and one branch line are put forward for construction, named Bahan Lake line, Bayan Lake line, Hetongchahan Lake line, Subei Lake line, Aomubai Lake line, Haolebaoji Lake line, and Huhe Lake branch line. The total length of the water transmission line is 127.23 km.

4. Discussion

4.1. Advanced Treatment Capacity of the Mine Water

Among the 6 mines in Wushenqi, No.2 Nalin River Mine, Yingpanhao Mine, Bayangaole Mine, and Menkeqing Mine have their own waste water treatment plants, while Muducaideng Mine and Hulusu Mine share one waste water treatment plant. Nalin River Mining Area also has other four waste water treatment plants. Existing conveyance infrastructure for unconventional water and water diverting from Yellow River can be seen in Appendix B. Under the current situation, the treatment capacity of the two mining areas of the mine water discharge is 58.4 million m^3. From the view of the overall capacity, the treatment plants have enough capacity to ensure that there is enough good water for use after treatment of the mine water. In the region, after deducting the self-used water, the treatment capacity of Nalin River Mining Area is slightly insufficient, while the treatment capacity of Hujierte Mining Area is abundant. It is necessary to send part of the mine water from Nalin River Mining Area to Hujierte Mining Area for treatment through the mine water pipelines. In the future, with the continuous increase of the mine water, Baijia Lake advanced water treatment plant needs to be built to increase the treatment capacity in Nalin River Mining Area.

4.2. Water Supply Capacity to the Lakes

If the actual utilization of mine water is not considered in the year 2019, the available water supply of the mine water of No.2 Nalin River mine will be 6.64 million m^3 and that of Yingpanhao Mine will be 5.76 million m^3, which can fully meet the ecological water requirement of Haolebaoji Lake, Aomubai Lake, and surrounding small lakes, and the redundant water can be used by enterprises in Nalin industrial zone or be sent to the mine water pipelines. The total ecological water requirement of Bayan Lake, Subei Lake, Kuisheng Lake, Hetongchahan Lake, Muken Lake, and surrounding small lakes is 10.02 million m^3, and the total available mine water supply capacity of 4 coal mines, namely Hulusu, Menkeqing, Muducaideng, and Bayangaole, is 23.35 million m^3, which can fully meet the lakes' water supplement and have the surplus water for the enterprises of Tuke industrial zone. The diversion port can be set at the right position of the Yellow River Diversion Project to supply water to Bahan Lake. The amount of water from the Yellow River Diversion Project is 27.29 million m^3, which can fully meet the water supplement of 5.83 million m^3 of Bahan Lake, and the remaining water can be used by enterprises in the Tuke industrial zone.

In addition, by making full use of 27.29 million m^3 of water diverted from the Yellow River Diversion Project and using it for industrial water demand of Tuke industrial zone nearby, part of the mine water can also be used for ecological environment water supplement, replacing the water from the Yellow River. As far as the current situation is concerned, the total surplus of mine water and Yellow River water is about 30 million m^3. Under the condition of making good use of the Yellow River water, the mine water can fully meet the ecological water supplement of the lakes. By 2030, the mine water will increase, and the ecological water can be met.

4.3. Water Quality of the Mine Water after Advanced Treatment

According to relevant research [37], the quality of mine water in Dongsheng Coal Field belongs to the medium-good type: class III groundwater. Based on the utilization practice of the advanced treatment mine water of the Menkeqing Mine, supplying water to the wetland of the relict gull reserve, the mine water after advanced treatment could meet the requirements of the Relict Gull reserve. After receiving the advanced treatment mine water, the water quality of the relict gull reserve still reached the class III standard of surface water according to the test of water samples on 18 March 2014 and 19 November 2020. In 2014, the water inflow from Pojianghaizi Mine was added to Tao-A Lake after sedimentation, and relevant research data showed that there is no significant difference between the water quality of Pojianghaizi Mine and that of the main breeding places of the Relict Gull reserve [38]. The above practices show that, mine water after advanced treatment is a high-quality unconventional water source.

Above all, it is also true that, on the basis of the relevant requirements of China and Inner Mongolia Autonomous Region's water-saving action implementation plan, on the premise of meeting the requirements of water quality, the treated mine water should be included in the regional unified allocation of water resources.

5. Conclusions

For the study area of Wushen Banner of Ordos City, Inner Mongolia Autonomous Region of China, this study analyzes the questions of the superfluous mine water and the lakes in urgent need of protection. The results are as follows:

1. A reasonable allocation and utilization mode of mine water aimed for lake water ecosystem protection is proposed.
2. The important lakes can be divided into three classifications according to their ecological protection goals. It is necessary to find suitable water supply sources and sufficient water quantity, and also ensure certain water quality.
3. There are about 46.7 million m^3 of water that can be adjusted to reach the utilization in 2020, and it is urgent to integrate the mine water into the regional unified allocation to find a reasonable and efficient utilization way.
4. The mine water inflow of the 6 coal mining enterprises in Wushen Banner in 2030 is about 74.53 million m^3, and it may be 103.7 million m^3 in 2030 with 9 coal mining enterprises. The available amount of mine water reached 57.17–81.97 million m^3 in 2030 in the ideal state. That is to say, it is enough to meet the water quantity that lakes need if priority is given to lake ecology replenishment. Meanwhile, the water quality of mine water after advanced treatment could meet the requirements of the lakes, and the treatment capacity is enough now and also in the future.
5. The water supplement path and the water quantity is established. Using GIS software, the pipelines of ecological water supply and transmission project aimed for the important lakes are arranged. It is composed of six main water transmission pipelines and one branch line, and the total length of the water transmission line is 127.23 km. Thus, it forms the reasonable allocation plan of the mine water for the important lakes.

The water allocation plan can provide an idea for improving the ecological environment of regional lakes, and it can also improve the efficient utilization of coal mine water and the regional water resource allocation.

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Appendix A. Forecast Amount of Industry and Total Water Demand in Different Years in Wushen Banner

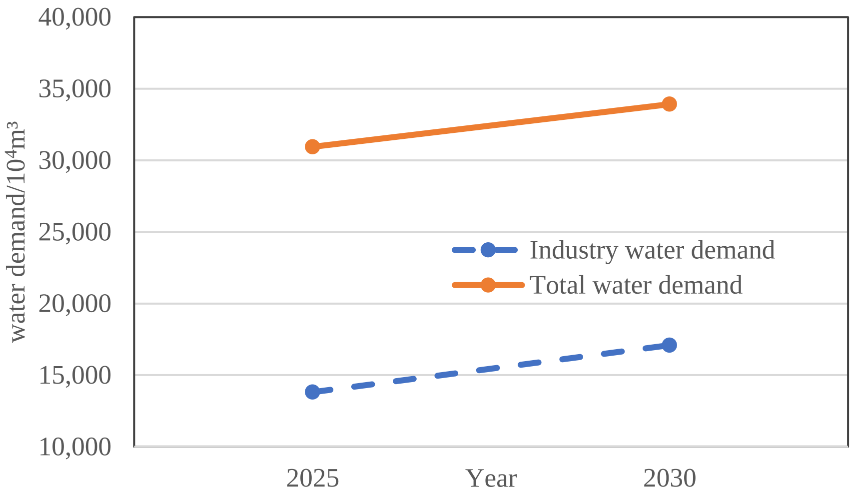

Figure A1. Forecasted amount of industry and total water demand in different years in Wushen Banner.

Appendix B. Existing Conveyance Infrastructure for Unconventional Water and Water Diverting from Yellow River

Wushen Banner has 4 mine pipelines and infrastructure to convey unconventional water, including mine water and recycled water. There are pipelines between the mines and the industrial zone. The pipeline of mine water utilization project of Nalinhe mining area starts from mine water treatment stations of No.2 Nalin River and Bayangaoleng and Yingpanhao mine plants to deliver mine water to the Nalinhe comprehensive water treatment plant. The comprehensive utilization project of Hujierte mine water transports the mine water from Muducaideng, Menkeqing, and Hulusu mine plants to Tuke artificial lake, through pipelines and pumping stations. The existing conveyance routes for mine water have connected the 6 mine plants and the 3 industrial zones.

The Yellow River diversion pipeline enters Wushen Banner from Ejin Horo Banner, and it is 18 km long in Wushen Banner. See Figure 1 for detailed pipelines. These water conveyance projects partially solve the problems of water conveyance and water use in industrial zones and coal mines.

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