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Targeting the Influences of Under-Lake Coal Mining Based on the Value of Wetland Ecosystem Services: What and How?

Huping Hou [1,2], Zhongyi Ding [3,4,*], Shaoliang Zhang [1,2,*], Zanxu Chen [3], Xueqing Wang [3], Aibo Sun [3], Shi An [3] and Jinting Xiong [2]

[1] Engineering Research Center of Ministry of Education for Mine Ecological Restoration, China University of Mining and Technology, Xuzhou 221116, China
[2] School of Environment Science & Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China
[3] School of Public Policy and Management, China University of Mining and Technology, Xuzhou 221116, China
[4] Research Center for Transformation Development and Rural Revitalization of Resource-based Cities in China, China University of Mining and Technology, Xuzhou 221116, China
* Correspondence: dingzhongyi@cumt.edu.cn (Z.D.); slzhang@cumt.edu.cn (S.Z.); Tel.: +86-138-5214-1910 (Z.D.)

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Abstract: Under the growing restrictions of the Chinese eco-environmental policies, the impact of under-lake coal mining on wetlands is receiving increasing attention from both coal mining enterprises and local governments. This paper focuses on the impact of under-lake coal mining on the Nansi Lake wetland from 1991 to 2021. Field measurements, resident surveys, and remote sensing inversion were comprehensively employed to quantitatively assess the impact. The calculation of the assessment indicators refers to the elastic coefficient, the information for which comes from four major categories of ecosystem service values (ESVs) and eight sub-ESVs. According to the results of the remote sensing interpretation and inversion, by 2021 the range had enlarged by 32.3 km^2, and the water depth had increased by 1.9 m in the mining-disturbed area relative to 1991. The ESV fluctuations in the Nansi Lake wetland also exhibited a generally increasing trend over time. Our results show that the under-lake mining disturbs the ESVs, but the disturbance is not sufficient to result in significant consequences. Based on the data analysis, we suggest several well-directed, appropriate restoration strategies to achieve the desired objectives and target the response of the ESV changes. Such measures will help to relieve some of the anxiety and concern about the wetland changes caused by the under-lake mining.

Keywords: under-lake coal mining; ecosystem service value; ecosystem protection; Nansi Lake wetland

1. Introduction

Wetlands host complex ecosystems that support diverse natural functions and provide essential services to human society [1,2]. Ecosystem services refer to the actual and potential benefits provided by ecosystems to humans, either directly or indirectly [3–5]. The ecosystem service valuation is an approach with which to quantify and assign economic value to ecosystem goods and services and their functions. Due to the growing demand for and overexploitation of natural resources, the structure and function of an ecosystem are severely affected at the local scale [6,7]. The ecosystem services valuation is in decline, negatively impacting human life. Wetland areas are affected by economic and political initiatives, and the ecosystem services valuation has attracted increasing public attention [8–10]. The assessment of the wetland ecosystem services evaluation leads to a deeper understanding of the operational processes and the internal mechanisms of wetland ecosystems and provides a clearer understanding of the importance of ecosystem services to human welfare. The ecosystem services evaluation provides the basis for establishing ecological compensation standards, the participation of stakeholders, and the management decision making [11].

Under-lake mining significantly influences aquifer connectivity and surface flows via subsidence disturbance [12]. To protect the sensitive eco-environment and ensure the delivery of ecosystem services, it is essential to quantify the transmutation of the ecosystem in order to develop ecological compensation criteria and a decision-making basis [11,13]. Recently, an intense discussion on the spatial-temporal dynamics of wetland ecosystems was initiated in China; it stemmed from a strict eco-environmental policy against the impact of under-lake mining activity [14,15]. A critical evaluation involves how under-lake mining impacts the wetland ecosystem [16]. An ecological assessment of the nexus between the wetland ecosystem and the impacts suffered should involve the selection of appropriate indicators and attributes [17]. However, spatially and temporally examining and quantifying the variability of the impacts has proven difficult. Scholars have proposed quantifying the ecosystem services to grasp the variability [11,18].

Numerous studies have adopted an ecosystem services framework with an economic valuation to assess the major wetland services [19]. The criteria for evaluating the wetlands ecosystem services are based on the wetland type, scale, and semi-independent indicators [20,21]. The ability to provide ecosystem services is affected by the wetland's size, the environmental conditions, the quality, and the socioeconomic environmental surroundings [22,23]. Several studies have integrated the millennium ecosystem assessment (MEA) and other assessment indicators to obtain comprehensive evaluation indices [24–26]. Using indicators relevant to wetlands, a three-level (good, medium, and poor) rapid assessment method has been proposed to demonstrate the ecosystem capacity in the Wimmera area [27].

Various methods have been used to determine the value of wetland ecosystem services [28], including the market value method [29], the carbon tax method [30], the contingent value method [31], and the meta-analysis method [32,33]. The US Environmental Protection Agency (US EPA) summarized 16 rapid assessment methods for diverse wetlands. Based on direct extrapolation from the value per unit area, these techniques have been used to analyze services at spatial scales such as the province and river basin scales [33]. These studies provide a reference for the classification of wetland ecosystem services and the methods for calculating their value.

Some researchers have explored the indicators related to the value of wetland ecosystem services at different scales, such as land use. Based on land use changes and an integrated valuation of ecosystem services, some scholars have investigated the relationship between one ecosystem service and others [34]. The impacts of land use change on ecosystems and ecosystem services have been investigated through integration with the economic analyses of such services. The knowledge of the changes in the spatial distribution of wetland land use/land cover changes over time is essential for the monetary breakdown of ecosystem services [35]. As a result, the land use/land cover data are used to derive indicators for the ecosystem functions [25]. In addition, this understanding implies necessary restrictions on or prohibition of harmful activities in wetlands, which probably include mining [36].

In addition to the methods described above, spatially explicit integrated modeling efficiently quantifies ecosystem services, biodiversity, and land use. Integrated models, such as the integrated valuation of the ecosystem services and the tradeoffs (InVEST), the artificial intelligence for ecosystem services (ARIES), and the land utilization and capability indicator (LUCI) models, have been well used to quantify and predict regional/basin ecosystem services [37–39]. Some studies discussed the potential benefits of using a geographic information system (GIS) for decision-making support [40].

No other land use has raised more disputes than under-lake mining, specifically when the aim is to achieve the full ecological function of the wetland [41]. However, little research has explicitly illustrated the impact of under-lake mining activities on the value of the ecosystem services. As is well known, under-lake coal mining will reshape the lake's form, such as by enlarging the area and deepening the depth. However, little research has been conducted on the trend and extent of the subsidence and its impact on the ecosystem services. Therefore, estimating the variations in the ecosystem services in a coal mining-disturbed wetland is feasible from the perspective of ecological evaluation.

Following this way of thinking, in this study the Nansi Lake wetland was chosen as the research area. Nansi Lake is the sixth largest freshwater lake in China and the second largest freshwater lake in the Huai River Basin in eastern China. Coal extraction beneath the lake has been conducted for almost 30 years. A quantitative valuation of the wetland ecosystem services is essentially undertaken for a tradeoff between the sustainable economic output of the mine and the protection and use of the wetland. We argue that ongoing monitoring and mitigation of the impacts on the lake are critical for balancing the regional ecological conservation and the resource development.

The specific objectives of this study are as follows: (i) to observe the relationship between the wetland shift over a period and the longer-term mining activities; (ii) to identify the current changes of the wetland ecosystem services; and (iii) to gain an insight into the influence of under-lake mining in the Nansi Lake wetland and to provide insights into the gaps between the local government and the enterprises regarding decision making.

2. Study Area, Data, and Methodology

2.1. Study Area

The Nansi Lake wetland (116°34′–117°24′ E, 34°27′–35°20′ N) is located in the northern part of the Huai River Basin in eastern China. It is the sixth largest freshwater lake in China and the most prominent natural surface water reservoir in Shandong Province (Figure 1). The lake covers an area of 1289 km^2 and is a vital water delivery channel and storage lake for the South-to-North Water Diversion Project. Apart from within the Beijing and Hangzhou Channel, the mean water depth of the lake is nearly 1.5 m. The lake's capacity is approximately 6.37×10^9 m^3, with radial drainage from 54 rivers. The lake is a shallow, open, plain grassland lake during flooding. The water flows from north to south and to the ocean via the Huai River. The lake experiences a warm temperate monsoon climate, with an annual average temperature of 13.7 °C. The yearly average rainfall is 550–720 mm, and almost 60% of the precipitation occurs during the rainy summer months. The annual average natural runoff is 2.96×10^{10} m^3.

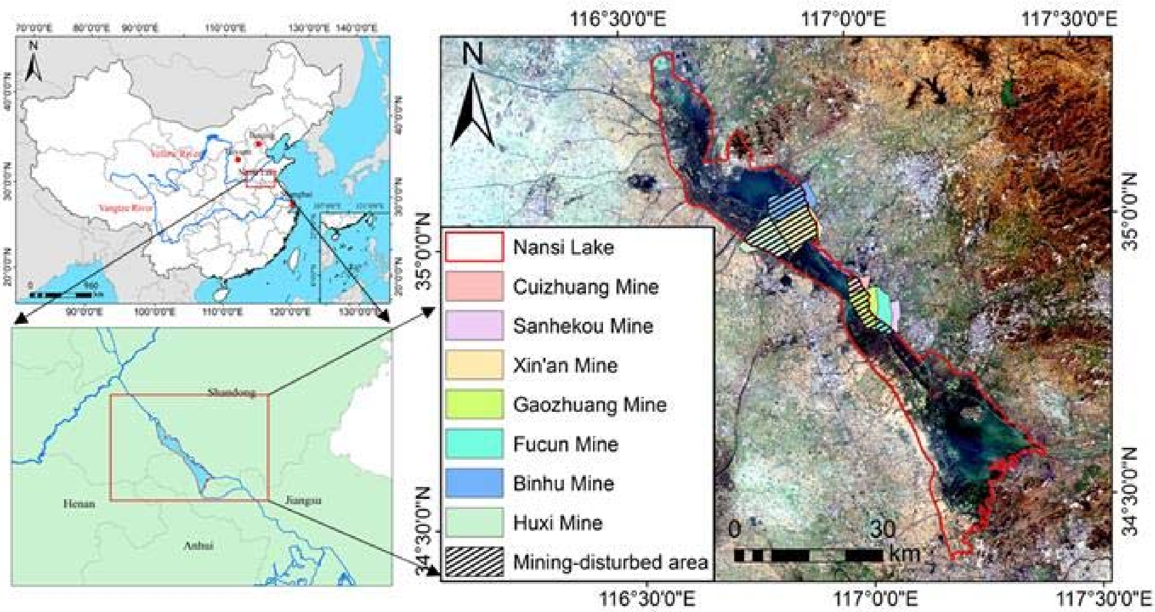

Figure 1. Location of Nansi Lake and the mining-disturbed area.

Seven coal mines are being mined underneath Nansi Lake, and the exploitation rights are owned by the Zaokuang Mining Group Co., Ltd. (Zaozhuang, China). The seven coal mines are the Cuizhuang mine, the Fucun mine, the Binghu mine, the Gaozhuang mine, the Sanhekou mine, the Huxi mine, and the Xinan mine. The mining-disturbed area is 159 km^2; it is an overlapping area between the Nasi Lake and the coal mining area (Figure 1). The coal-bearing strata in this area are the Permian Shanxi Formation and the Carboniferous Taiyuan Formation. There are 21 coal seams in total, including 4 minable coal seams: 3$^{\#}$, 12$^{\#}$, 14$^{\#}$, and 16$^{\#}$. The average total thickness of the coal seams is 5.78 m, accounting for 82% of the total thickness of the minable coal seams. The texture of the coal seam is of a medium type. Fully mechanized longwall mining with top coal caving and thin seam comprehensive mechanized mining techniques are used. The mining of multi-coal-seam strips is conducted at depths of −90 m to −1500 m. The annual total production capacity is 12 million metric tons. An area of 170.73 km^2, which occupies about 75% of the overall mining area, is classified as a mining-disturbed area within Nansi Lake (Figure 1). In 2020, coal mining contributed 61.40% of the local gross domestic product (GDP) (Statistics Bureau of Weishan County, 2021). The remaining mining life of the mines is 13.1–76.1 years.

2.2. Datasets Used

Assessments of extensive wetlands are often challenging because of the heterogeneity of the various wetland cover types [42]. Two types of data, i.e., Landsat thematic mapper TM images and a sentinel-1 image, were used to analyze the wetland's temporal and spatial changes. Based on availability and quality, cloud-free Landsat TM images (9 May 1991, 25 May 1997, 10 May 2003, 26 May 2009, 25 April 2015, and 27 May 2021) were downloaded from the Geospatial Data Cloud site, Chinese Academy of Sciences (http://www.gscloud.cn, accessed on 1 October 2021). These Landsat TM images have a pixel size of 30 m × 30 m for the spectral bands used. In addition, a sentinel-1 image (29 May 2021) was downloaded as a reference for the interpretation and inversion.

These images were rectified using a 30 m resolution digital elevation model in the ArcGIS Environment for Visualizing. The image software (ENVI 5.3) was used to conduct the radiometric and atmospheric corrections and the pixel-based supervised image classification.

The ground truth data (50 points) from a field survey were used for the supervised land use classification and water depth inversion verification. Ecosystem services and ecological environmental demand surveys were carried out in 17 villages along the lake. Other auxiliary eco-environmental data, such as air quality data, were obtained from various administrative departments, such as the local forestry bureau and the Bureau of Wetland Nature Reserves. Some socioeconomic data were collected from the statistical yearbooks of Weishan County and Shandong Province. The vector data for the boundaries of the coal mining were obtained from the Zaokuang Mining Group Co., Ltd. (Zaozhuang, China).

2.3. Methodologies

Three steps were employed to examine the influences of the mining activities. This section describes the remote sensing (RS), GIS, and site survey methods, and a schematic diagram illustrating the methodology is presented in Figure 2.

2.3.1. Traditional ESV from Land Use Interpretation

The merger of Landsat images has the powerful capacity of time-series analysis and has been proven effective for observing long-term land use changes [43]. In this study, the most common land use types were selected for the classification. The land use was classified into six types: (a) lake, (b) river, (c) swamp, (d) irrigated paddy field, (e) raised field fishpond, (f) building land, (g) forest land, and (h) other land. The kappa coefficients of the classification results were 0.93 for 1991, 0.93 for 1997, 0.93 for 2003, 0.89 for 2009, 0.94 for 2015, and 0.90 for 2021.

Based on the literature on the millennium ecosystem assessment indicator, the ecosystem services (ESs) were classified as provisioning, regulation, support, and cultural services. These values provide a standard set of units and allow a comparison across services. The general calculation methods are described below.

The framework for calculating the value of the ecosystem services is embedded with three evaluation methods: the market value, the replacement cost, and the benefits transfer methods.

The market value method is suitable for calculating the ESV of the aquatic product and is expressed as follows:

$$V_p = \sum_{i=1}^{n} V_{pi} \times \sum_{i=1}^{n} S_{pi} \times Y_{pi} \times P_{pi}, \quad (1)$$

where n is the number of product types; V_p is the sub-ESV; V_{pi} is the value of the i^{th} product; S_{pi} is the area of the i^{th} product; Y_{pi} is the unit yield of the i^{th} product; and P_{pi} is the unit value of the i^{th} product.

The replacement cost method is suitable for calculating the carbon sequestration, oxygen release, climate regulation, water regulation, and habitat value and is expressed as follows:

$$V_p = Q_r \times P_r, \quad (2)$$

where Vr is the sub-ESV; Qr is the amount; and Pr is the equivalent cost of planting, generation, and protection.

The replacement cost method is suitable for calculating the ESV of biodiversity conservation and scientific research and education and is expressed as follows:

$$V_p = P_r \times S_r, \quad (3)$$

where V_p is the sub-ESV; P_r is the value of the biodiversity conservation or benefit per unit area; and S_z is the area.

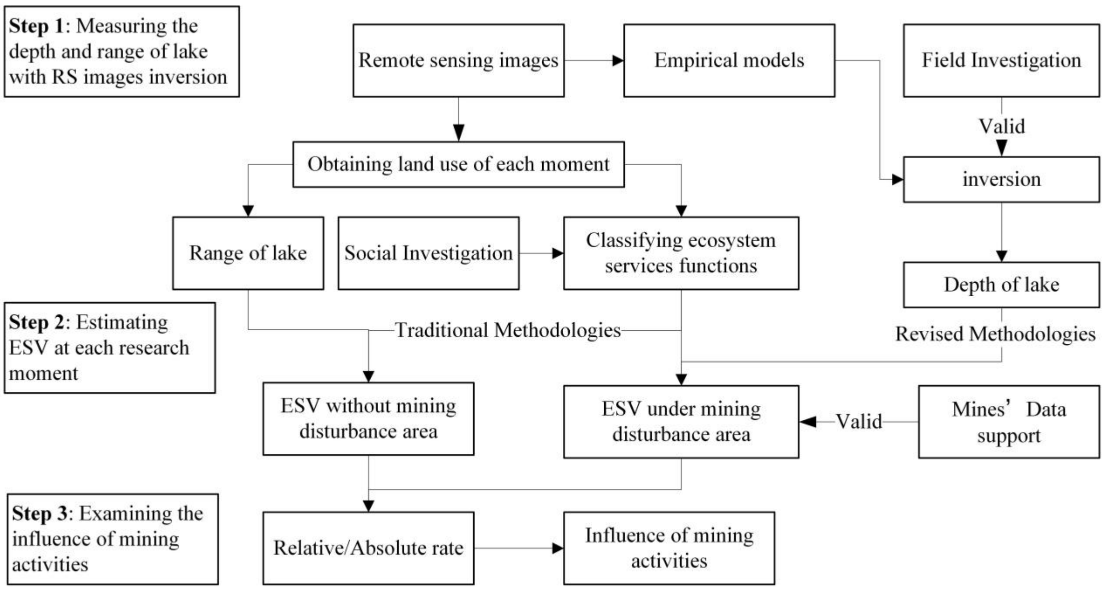

Figure 2. Schematic diagram showing the research process.

2.3.2. Revised ESV with Water Range and Depth from RS Image Inversion

Traditionally, the ESV analysis of a wetland focuses on the per unit area estimate, using the land cover type and the scaled use of the areal extent of each land cover type [44]. In contrast, when considering the influence of mining activities, it is a revised method to help visualize the truth of the under-lake mining. Additional estimates (lake range and depth) should be added, notably for the volume calculation involved.

(1) Water range of the lake

Using Landsat images, the water range of the lake was easily identified [45,46].

(2) Water depth of the lake

The water depth was measured using the Landsat images and a statistical inversion model [47]. An inversion model was established by conducting regression analysis of the reflectivity of the image pixels and the water depth [48]. The Landsat TM bands 3 (0.62–0.69 μm), 4 (0.76–0.90 μm), 5 (1.55–1.75 μm), and 7 (2.08–3.35 μm) have generally been reported to be the best band combination for wetland detection [49].

A linear regression model was established to simulate the water depth measured at 120 randomly selected sampling points, of which 65 points were used as training samples and 55 points were used as testing samples [50]. The independent variables were used to establish a multiple linear regression model using Equation (4) [51].

$$L_i = L_{si} + C_i R_{bi} e^{f k_i z}, \tag{4}$$

where L_i is the radiation value of the ith band, L_{si} is the radiation value of deep water, R_{bi} is the bottom reflectance, k_i is the attenuation coefficient of the water body, f is the path length in the water, and z is the lake's depth. C_i is a parameter related to solar radiation, atmospheric and water surface transmittance, and water surface refraction.

By synthesizing single-band and dual-band data into multi-band data, Equation (5) was derived. A group of Z-x_i values were measured from the ith band image of the sensor. The coefficients (A_0, ... , A_n) were obtained using the ordinary least squares method [52]. Z is the depth.

$$Z = A_0 + A_1 X_1 + A_2 X_2 + \cdots + A_n X_n. \tag{5}$$

2.3.3. Characterization of Influence Indicators from Mining Activities

In economics, elasticity can be quantified as a ratio to measure the percentage change of one variable in response to a change in another variable. Here, the former variable is specified as mining. The coefficient is defined as follows:

$$E_i = \frac{\partial y}{\partial x} \frac{y}{x}, \tag{6}$$

where E is the elasticity, which is the same as a rate; x and y represent the variables, and i denotes time.

Equation (6) is expanded because the different groups introduce the same concept. The unscaled elasticities are often depicted as an elasticity matrix. Then, the elasticity matrix is defined as follows:

$$E = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \cdots & \frac{\partial y_1}{\partial x_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial y_n}{\partial x_1} & \cdots & \frac{\partial y_n}{\partial x_m} \end{bmatrix}. \tag{7}$$

In this paper, E is an n × n matrix, and the ESV has been divided into five classes. Eigenvalues and eigenvectors are used to analyze the change in the ESV over time. The ESV is examined at yearly intervals. The goal is to determine the long-term dynamics of the ESV, that is, the direction and extent of the influence of the mining on the change in the ESV of Nansi Lake.

To answer the questions posed in this study, the eigenvalues and eigenvectors of the matrix E above are examined. Here, the eigenvalues λ are denoted as $[\lambda_1, \lambda_2, \cdots, \lambda_n]$. The larger the eigenvalue, the richer the information. The eigenvalue has two situations Equation (8): (1) if >1, extend the vector; (2) if <1, shrink the vector [53]. The geometric meaning is that the eigenvectors are only expanded and contracted by the transformation of matrix E while the direction remains unchanged.

$$|\lambda_{\max}| = \begin{cases} \text{help to enlarge the change} & > 1 \\ \text{barrier to integrated change} & < 1 \end{cases}. \quad (8)$$

The eigenvector is the principal eigenvector, which corresponds to the eigenvalue with the largest modulus. The principal eigenvector gives the long-term distribution of the ESV through the sub-ESVs. Therefore, the selected eigenvector is a possible indicator for characterizing the mining influence.

$$v_{\lambda_{\max}} = [v_1, v_2, \cdots, v_n]^T. \quad (9)$$

$v_{\lambda_{\max}}$ is the principal eigenvector and is defined in Equation (9). $v_1, v_2, \cdots, v_n$ are the elements, which are regarded as a numerical value characterizing the approximate contribution. If $v_i > 0$, the contribution is positive; otherwise, the effect is negative.

3. Results

3.1. Land Use Types in the Wetland during Different Periods

In a realistic assessment of the ecosystem service situation, the services provided by the diverse ecosystems and land cover types should be considered. A land use category is desirable for estimating Nansi Lake's ecosystem services. Based on a field investigation and an analysis of the historical documents, the land use types were divided into lake, river, swamp, irrigated paddy field, raised fishpond, building land, woodland, and other land. The extraction of the land use categories was conducted through the supervised classification of the remote sensing images. Before the classification, training samples for each category were selected according to the field survey. The categories of land use types in Nansi Lake and the mining-disturbed area are described in Tables 1 and 2.

The natural wetland area decreased rapidly, with the reduced area accounting for 43.4% and 15.3% of Nansi Lake and the mining-disturbed area, respectively. However, the lake area increased by 90 km^2 from 1991 to 2021, and the mining-disturbed area increased by 32.3 km^2. The constructed wetland area increased rapidly, with an increase of 43.8% in Nansi Lake and 16.4% in the mining-disturbed area. However, the areas of the irrigated paddy fields and raised field fishponds in Nansi Lake increased by 8.3% and 35.5%, respectively. The area of the irrigated paddy fields decreased by 5.2% in the mining-disturbed area, and the area of the raised field fishponds increased by 21.6% in the subsidence area.

Table 1. Areas based on the value of wetland ecosystem services in Nansi Lake from 1991 to 2021 (km^2).

Wetland Types		1991	1997	2003	2009	2015	2021
Natural wetland	Lake	520.6	475.4	469.4	464.3	433.4	430.7
	River	26.8	50.6	44.1	52.3	66.5	54.7
	Swamp	555.7	525.8	401.2	196.5	93.7	59.7
	Total	1103.2	1051.8	914.8	713.2	593.7	545.2
Constructed wetland	Irrigated paddy field	97.9	144.1	146.2	163.2	232.3	204.8
	Raised field fishpond	5.3	23.5	167.9	356.3	415.0	462.9
	Total	103.2	167.6	314.2	519.5	647.4	667.8
Non-wetland	Building land	27.4	26.9	17.9	18.5	24.6	27.6
	Woodland	7.8	7.1	7.9	10.4	8.0	11.2
	Other land	46.8	35.0	33.7	26.9	14.9	36.7
	Total	82.2	69.1	59.7	55.9	47.5	75.6

Table 2. Areas based on the value of wetland ecosystem services in the mining-disturbed area from 1991 to 2021 (km^2).

Wetland Types		1991	1997	2003	2009	2015	2021
Natural wetland	Lake	69.0	78.1	86.4	93.4	103.9	101.3
	River	9.5	10.0	9.0	9.7	7.9	5.1
	Swamp	59.6	42.9	34.1	14.6	11.5	7.4
	Total	138.2	131.1	129.6	117.8	123.4	113.8
Constructed wetland	Irrigated paddy field	12.8	20.4	14.3	10.1	13.1	4.5
	Raised field fishpond	0.1	0.4	11.7	25.4	18.3	34.6
	Total	13.0	20.8	26.1	35.5	31.5	39.1
Non-wetland	Building land	2.7	2.1	2.7	2.5	3.0	2.6
	Woodland	0.6	0.0	0.03	2.2	0.0	1.8
	Other land	4.2	4.8	0.4	0.6	0.8	1.4
	Total	7.6	6.9	3.2	5.4	3.9	5.8

Under-lake mining caused subsidence in Nansi Lake. A schematic diagram illustrating these changes is shown in Figure 3. The subsidence of the lake bottom caused by the coal mining directly affected the water capacity, increasing the water depth and expanding the water surface range. Moreover, this phenomenon benefited irrigation and shipping. The land use changed dramatically, significantly influencing the wetland ecosystems and determining the wetland's sensitivity to human disturbances [54–56]. We identified six land use types clustered into two main categories: mining-disturbed and non-disturbed areas.

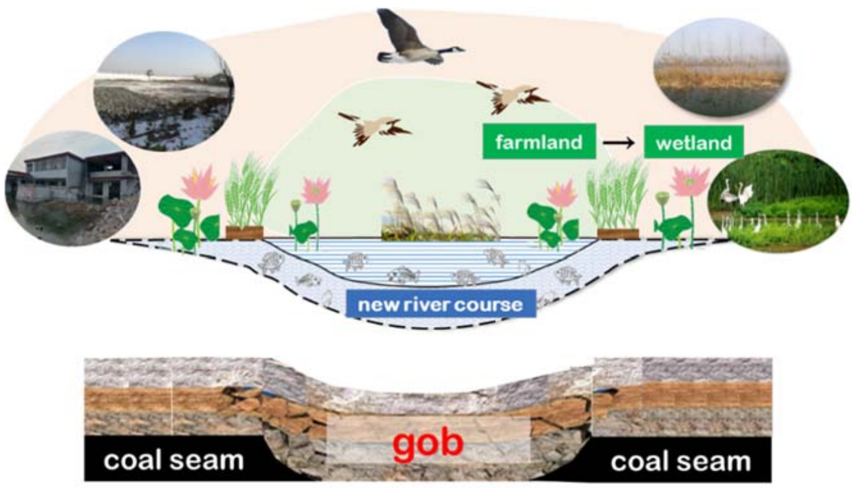

Figure 3. Changes in Nansi Lake due to under-lake mining.

3.2. Water Depth of the Wetland in Different Periods

As has been observed in recent decades, lake surface conditions, such as evaporation and water level, respond dramatically to climate change [57]. Few studies have discussed the influences of coal mining under the lake in the plain area on the lake's water depth. With increases in coal production in the future, the lake's response will impact the lake ecosystems, changing the water quantity and quality, food provisioning, recreational opportunities, and transportation.

Scholars have found that the multi-band combination model for freshwater lakes has a higher progress and more minor errors than the water depth inversion model [58]. In the multi-band model, most of the gray values of each band are processed logarithmically, and a linear regression model is established to simulate and predict the water depth of each region [50].

Twenty of the thirty-three sampling points were randomly selected as the training set, and the remaining thirteen were used as the testing set to construct the regression model. A linear regression model was established by combining multiple bands with the significant correlation coefficients. The model with the largest correlation coefficient (R^2) and the lowest mean square error (MSE) was selected as the ideal model. The model was constructed using SPSS19, and the regression equation when the significance level is 0.05 is

$$H = [32.804 + 3.625 * \ln(b_1) - 10.074 * \ln(b_2) + 9.244 * \ln(b_3) + 16.638 * \ln(b_4)], \quad (10)$$

where H is the water depth, and b_1, b_2, b_3, and b_4 are the gray values of the blue, green, red, and near-infrared bands.

The established linear regression model has an R^2 value of 0.903 and an MSE of 0.055, based on the training set. Based on the testing set, the R^2 value is 0.886, and the MSE is only 0.134. It has an excellent fitting effect and high precision. The water depth data are presented in Table 3.

Table 3. Nansi Lake water area depths from 1991 to 2021 (km^2).

Water Depth (m)	1991	1997	2003	2009	2015	2021
$0 \leq 1$	179.6	181.7	69.2	42.7	54.8	93.8
$1 \leq 2$	239.0	172.7	144.3	41.0	131.6	122.1
$2 \leq 3$	80.3	82.2	141.8	144.2	117.2	134.3
$3 \leq 4$	21.6	38.7	113.4	92.9	85.4	21.9
$4 \leq 5$			0.4	107.6	40.7	4.2
≥ 5				35.6	3.5	54.2

As the Nansi Lake region is a high phreatic area, the mining activity underneath the lake has caused the lake bottom to subside. The golden 10 years of the coal industry in China were from 2002 to 2011. The lake bottom subsidence has increased the water depth, which is consistent with the experimental research on the coal mining under Nansi Lake [59]. In 2022, a new golden decade will begin. According to the results of the remote sensing inversion, by 2021 the water depth had increased by 1.9 m in the mining-disturbed area relative to 1991. Improving the lake depth monitoring will enhance our understanding of the lake's responses to changes in the mining activities.

3.3. Calculating the ESV of Nansi Lake

As was mentioned in the previous chapter, a social investigation was conducted to identify the vital ecosystem services using the free-listing method based on the millennium ecosystem assessment and the previous studies. The survey objects were 160 fishers, villagers, village cadres, and employees of the enterprises and the government workers along the lake. The social investigation also allowed us to easily gather data on the quantity and the net value of the local production to measure the value of the ecosystem services.

Based on the survey results, the ecosystem services included four major services (provisioning, regulating, supporting, and cultural services), which were further divided into eight sub-services. The provisioning services of Nansi Lake primarily refer to the aquatic products. The regulation services mainly include atmospheric regulation, microclimate regulation, water regulation, and water purification. The support services comprise biological habitat functions and biodiversity conservation. Similarly, the cultural services consist of tourism, scientific research, and education. The four primary service values are abbreviated as ESVp, ESVr, ESVs, and ESVc.

The overall ESV of Nansi Lake was estimated to be CNY 4.667–8.850 $\times 10^9$. Temporally, the fluctuations in the ESV exhibited a generally increasing trend (Figure 4). Taking 1991 as the benchmark, the growth rate of the ESV over the past 30 years was 7.15–29.5%. The average annual growth rate of the ESV was 2.21%. Coincidentally, in keeping with the current development trend of wetlands in China, the overall trend remained stable and exhibited positive development (China's wetlands of international importance improving: white paper, 2022).

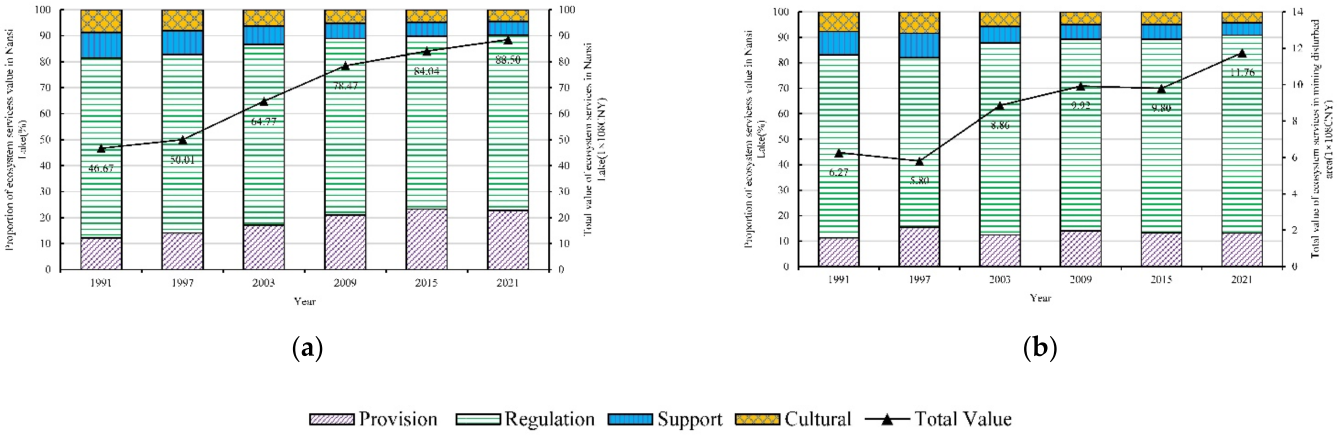

Figure 4. ESVs in Nansi Lake and the mining-disturbed area from 1991 to 2021. (**a**) Total value of ecosystem services in Nansi Lake, (**b**) Total value of ecosystem services in mining disturbed area.

In addition, the ESVr was the mainstay of the ESV, accounting for about 68.2% of the total ESV. Over the past three decades, the ESVr has increased significantly from CNY 3.2 33 $\times$ 10^9 to CNY 5.970 $\times$ 10^9, playing a dominant role in the increase in the total ESV. The ESVp continuously increased from CNY 5.69 $\times$ 10^8 to CNY 2.022 $\times$ 10^9, i.e., by 2.5 times. Its proportion of the total ESV also increased from 12.2% to 22.8%. The ESVr remained stable at around CNY 4.60 $\times$ 10^8. The amount of the ESVc was close to that of the ESVs.

3.4. Analysis of Influence of Mining Activity Based on the ESV

For the convenience of the analysis, the calculation results were truncated into two regions: the entirety of Nansi Lake and the mining-disturbed area. Based on the previous research results, the changes in the entirety of Nansi Lake and the mining-disturbed area from 1991 to 2021 were compared and analyzed. The following four components ultimately determined each state (Ei) in these changes. Matrix A is the elasticity coefficients deduced from the percent of the ESV changes of Nansi Lake and the mining-disturbed area (Table 4).

Table 4. Elasticity coefficients.

Sub-ESV	Elasticity Coefficients				
Provisioning services	0.139	0.051	0.035	0.033	0.230
Regulation services	−0.324	0.265	0.092	0.007	0.435
Support services	−4.500	0.273	1.000	−0.091	0.000
Cultural services	−0.027	0.364	0.267	0.500	−0.196
Total	−0.140	0.207	0.069	0.019	0.413

Using MATLAB, the eigenvalues and eigenvectors were determined using the command [V D] = eig(A). The results (effective eigenvalues and eigenvectors) are presented in Table 5.

Table 5. Eigenvalues and eigenvectors.

Eigenvalues	Eigenvectors
0.001	$[-0.843, -1.821, -3.009, 3.291, 1]^T$
0.175	$[-6.643, 3.668, -34.728, 24.787, 1]^T$
0.479	$[0.178, 1.264, -0.368, -7.263, 1]^T$
0.827 – 0.446i	$[0.686 + 0.093i, 1.058 - 0.133i, 3.184 - 5.731i, 3.417 - 0.221i]^T$
0.827 + 0.446i	$[0.686 - 0.093i, 1.058 + 0.133i, 3.184 + 5.731i, 3.417 + 0.221i]^T$

It should be noted that of the most significant importance to this analysis is λ_1 = 0.827–0.446i, i.e., the eigenvalue with the most considerable magnitude. For the obtained complex eigenvalues, the modulus part represents the scale enlargement, and the imaginary part represents the rotation angle. If the modulus of an eigenvalue is less than 1, then the mining influence on Nansi Lake exists but is insignificant. The impact is positive.

The corresponding eigenvectors can be further rescaled so that their entries sum to 1, namely (0.082, 0.127, 0.382, 0.409). The entries in this vector show each class's fraction of the ecosystem. The provisioning services accounted for 8.2% of the change, which was the lowest among the sub-ESVs. The support and cultural services contributed about 40% of the change and were relatively inelastic. The elasticity of the regulation services was intermediate, with a value of 12.7%.

The mining disturbance under Nansi Lake impacted the ESV, but it was not sufficient to produce significant consequences. This may be related to the small proportion (12.34%) of the mining-disturbed area in Nansi Lake, which results in the impact being insufficiently significant. In addition, some existing policies and practices can mitigate the effect on the ecosystem services and offer a better pathway through the ongoing transitions.

4. Discussion

4.1. Rationality of ESV Results

Many of the ecosystem services of the wetlands are intangible; thus, their actual value is hardly considered. Costanza made a significant contribution to calculating the ESV. However, the ESV of the wetland in this study may be different due to the scope of the under-lake mining. This paper provides an updated estimate based on updated unit ecosystem service values (in any unit) and land use changes due to under-lake mining and other factors. Even though the sub-ESV categories may be problematic, the calculations should collectively consider the sub-ESV accessibility. Local people harvest a wide range of valuable products from the lake, yielding 31.5 t/km^2 and 225 t/km^2 in 2019 and 2021, respectively [60]. Our analysis revealed that the highest benefit was generated from the ESVr (68% of the total ESV) of the Nansi Lake wetland, followed by the ESVp. Compared with the mean wetland referred to by Costanza, the Nansi Lake wetland provides an ESV of CNY 4.667–8.850 $\times$ 10^9, which is about 0.4–0.7 times higher than the 2800 USD/ha/year reported by Brander.

Accounting units help to highlight the magnitude of the public goods or common pool resources with a specific decision-making context. Estimating the relative contributions of the ecosystem services has been determined to be an essential part of changing the ESV [61]. While simple to understand and calculate, these results may gloss over the complexities of the services involved. However, we must continue to rely on unit ecosystem service values for the current estimates. Furthermore, aggregates of the analyzed results help us to assess the change scenarios of under-lake mining activity or to conduct meta-regression to produce more accurate calculations.

Another difference in the ESV results is due to the method of valuation. Any discussion of indicators immediately evokes debate about weights and preferences. However, any weight (structure) is likely to be criticized because assigning weights is a value-dependent process [62]. When preferring one type or several types of valuation methods, the greatest challenge is the inadequate knowledge regarding linking the ESV to the land use changes, especially for those that are non-marketed. However, our results are subject to methodological limitations. We show the long-term existence of benefits from the wetland and their differences, while considering the influence of the mining compared to that of the previous studies [63].

4.2. Possibility of Influence Strength of Under-Lake Mining

Another target of our work was to identify the influence of the under-lake mining that affected the ESV of Nansi Lake. Previous studies have shown that numerous factors may influence the ESV results. Significantly, the attribution of the wetland itself, including the wetland type and size, was the fundamental factor [64]. The socioeconomic development had the most significant impact on the ESV changes [65]. Multi-factor analyses of the impacts of under-lake mining could help in better understanding the possibility of the influence on the Nansi Lake wetland and in providing a foundation for future management.

As the socioeconomic drivers of the ecosystem changes intensify, the feedbacks between ecosystem services and human well-being become more complex. In this study, under-lake mining was one of the most important human activities in the Nansi Lake Basin. An indicator for estimating the scope of the influence of the mining subsidence was named the mining subsidence coefficient (MSC), which is defined as the subsidence area (m^2) per metric ton of coal production. According to the monitoring data for each mine, the MSC ranged from 0.2 to 0.6, with an average value of 0.35. The impact area of the under-lake mining was estimated to be 4.20 km^2.

The subsidence coefficient (q) was used to determine the collapse volume per ton of coal and then to calculate the collapse volume of the coal seam mining. According to the measured data, q was estimated to be between 0.65 and 0.75. In the case of repeated coal mining, q was 0.725. In addition, another influencing factor was the density of the coal, 1.30–1.40 g/cm^3. Based on this, it was estimated that a collapsed volume of 5.7×10^7 m^3 has been generated in the past 30 years. If the full height of all of the residual recoverable reserves (3.5×10^{10} t) was mined, a collapsed volume 4.6×10^8 m^3 of would be generated. These collapsed volumes will directly and permanently increase the lake's storage capacity.

Wetlands are already responding rapidly to climate change, which is well known. Analysis of existing data has shown that the most significant difference in the regulating ability of Nansi Lake between a normal year and a dry year is about 0.5 billion m^3. The limited regulating ability has led to the upper and lower water levels remaining the same during the past 30 years. However, after 2002, due to storage and diversion projects, industrial and agricultural water use, and other activities, the influx into the lake continued to decrease, and the surface water level continued to decline. The measured water level data confirm this change. Therefore, the contribution of climate change to the ESV of Nansi Lake is not apparent.

In summary, explanations for this discrepancy have been attributed to the following different processes: (a) under-lake mining expands the scope of the lake; (b) under-lake mining increases the volume of the lake; and (c) climate plays a negligible role on a small scale.

4.3. Implications for Regional Ecological Management

Most socioeconomic benefits from wetlands have been overlooked and undervalued because they have not been traded in the economic market nor integrated into decision making [66]. The decision-making problem is further compounded by limited knowledge and awareness among local governments and the public regarding the multiple wetland service values for different interests. China and Shandong Province have launched various sets of wetland conservation and restoration programs, and even compensation programs, which require more information about the ESV to support the relevant decisions [64]. Through quantitative assessment of the ESV and the effects of under-lake mining on the ESV, policymakers could select well-directed, appropriate restoration strategies to achieve the desired objectives and target the response to the ESV changes.

(1) Strategies for maintaining and improving the four services

Regulation services are the leading service function of Nansi Lake and are predicted to continue to grow. Measures such as restoring agriculture planting and breeding land to wetlands will help to stabilize and ensure the increase in regulation services. The subsidence of the lake bottom causes uneven and multi-point water depth variations. Timely dredging can ensure the connectivity and stability of the rivers to the lake's bottom and shorelines to improve the adjustment service function. Due to the imbalance of the water depth and the vegetation distribution, the water purification service is in a state of flux.

Restoring an appropriate density of aquatic plant communities, especially the shallow water plants, is necessary for maintaining a relatively stable purification capacity according to the changes in water depth. As was previously discussed, the assessment results encourage the development of ecological tourism, popular science education, entertainment, and other special industries in the subsidence areas.

(2) Monitoring the impact of under-lake coal mining on wetland ecosystem services

Regarding the need for timely assessment and early warning, acquiring real-time data on ESV changes is a prerequisite for developing an under-lake-related restoration strategy. In this study, various monitoring methods, such as fixed-point measurements, field investigation, discussion, and remote sensing, were used. Comprehensive ecological environmental surveys can provide essential data support for eco-environmental protection management. The conclusions based on the evaluation are significant for guiding and supervising mining enterprises in order to fulfill the primary responsibility of ecological protection and restoration. Such monitoring objectives may differ from those of other countries.

(3) Improving the assessment of the data gaps and the acceptability of the results

Although some valuable research results were obtained in this study, there are still some shortcomings, and further demonstration is needed for further acceptance by multiple stakeholders. More monitoring sites need to be added to the existing basis. Furthermore, building an entire set of processes and methods for monitoring wetland ecosystems is a more feasible solution. The monitoring content needs to cover land resources, as well as the ecological environment, wild animals, and plants in the wild.

5. Conclusions

Therefore, is it possible to sustainably extract coal from beneath a lake, such as Nansi Lake, while also achieving wetland ecosystem protection under China's strict environmental policies? Many factors indicate that the future of wetland ecosystems is shifting towards solutions that are resource-oriented and nature-based. Multiple targets besides coal production prompt governments and enterprises to gradually agree on the degree of impact on the wetland ecosystem. Over the past 30 years, the average annual growth rate of the ESV was 2.21% in Nansi Lake. The influence of the under-lake mining was positive but insignificant. Our results are encouraging and may help relieve some anxiety and concern about the changes to the wetland caused by under-lake mining.

Even though this paper used ESV changes to comprehensively reflect the impact of coal mining under the Nansi Lake, a series of detailed works should be continued on the ecological effects of under-lake mining, considering aspects such as the coal thickness and the mining methods.

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