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Assessing the Sustainability Impacts of the Xiaolangdi Dam: Land Use and Socioeconomic Change in the Middle and Lower Reaches of the Yellow River Basin

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Abstract: This paper assesses the sustainability impacts in the middle and lower reaches of the Yellow River in China after the Xiaolangdi Dam was constructed. Based on land use data interpreted from Landsat remote sensing images, covering the time period from 2000 to 2020 at 5-year intervals, this research uses a land dynamic attitude index and comprehensive index of land use degree to reveal the degree of land use type change in the study area and analyze the relationship between land use and social economy. The results show that urban and rural construction land is the land use type with the largest annual change rate, and the increase is most obvious from 2005 to 2010, growing by nearly 900 km^2. The six types of land use in the research area changed sharply from 2000 to 2010, with grassland and unused land showing the most significant change. On the whole, the dynamic attitude of comprehensive land use tends to be stable. The comprehensive index analysis of land use degree indicates that the study area has developed in the direction of urban settlement. Population and GDP are the main driving factors affecting the constant change in land use types in this region, in which population growth and rapid economic development are the main factors leading to the decline of grassland area, and are also the main driving factors for the expansion of construction land. The research results provide a scientific basis for sustainable land use and development in the middle and lower reaches of the Yellow River Basin.

Keywords: sustainability; Xiaolangdi Dam; Yellow River Basin; land dynamic attitude index

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1. Introduction

To address the temporal and spatial redistribution of runoff, to foster water resource development, and to enhance their adaptability to human requirements, human beings have undertaken the construction of dams, reservoirs, and water conservancy facilities along rivers. From a global perspective, the construction of dams assumes an increasingly significant role in flood control, sediment mitigation, navigation safety assurance, agricultural irrigation, and hydroelectric power generation [1,2]. For example, the United States built the Hoover Dam on the Colorado River, Brazil and Paraguay jointly constructed the Itaipu Dam on the Parana River, and Egypt constructed the Aswan High Dam on the Nile River, among others. These projects have provided significant energy and water security in support of the economic and social development of these respective countries [3–5].

Another important example of a major dam project is the Xiaolangdi Dam on the Yellow River in China. The Yellow River Basin originates from the peaks of the Bayankala Mountains in Qinghai Province, China, flows through the nine provinces of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, and finally flows into the Bohai Sea in Dongying City, with a total length of 5464 km and a total basin area of 795,000 square kilometers. As the middle reaches of the Yellow River flow through the Loess Plateau, its tributaries carry a large amount of sediment, resulting in the Yellow River having the world's highest sediment concentration. The middle and lower reaches of the Yellow River are the birthplace of the Chinese nation and one of the most important economic and cultural centers in Chinese history, meaning that the Yellow River is of great significance to Chinese history and culture. However, in order to reduce flooding, improve navigation, support irrigation for agriculture, and provide hydropower, a series of dams have been constructed along the Yellow River. One significant water conservancy project in the river basin, the Xiaolangdi Dam, was completed in 2000. The dam was designed to not only promote the socio-economic development of the middle and lower reaches of the Yellow River Basin but also protect ecology and the environment by providing ecological water replenishment.

While potentially creating huge economic and social benefits, these major water conservancy projects also inevitably change the surrounding vegetation conditions and can impact ecological processes and land use in ways that are both positive and negative [6]. To inform their continued use in development programs, and to help design more sustainable water conservancy projects, there is consequently a critical need to assess the long-term sustainability impacts of dams. Multiple assessment methodologies are potentially suitable for this purpose. A systematic and comprehensive identification method is a common, traditional evaluation method, but it requires a lot of accurate historical data. At present, remote sensing imaging has the advantage of providing large spatial scale and long time scale monitoring [7]. It provides a large amount of digital land use and ecological change information, so high-resolution satellite remote sensing images are widely used in land use, ecological environment investigations and dynamic monitoring research [8]. The process of land use change has a significant influence on ecosystem services and ecological landscape patterns [9–11]. Habitat patches, network structure, rational urban land use, and the development of species are closely related to regional land use structure and spatial layout changes [12]. At present, the assessment of land use change focuses on the characteristics and mechanisms of spatio-temporal evolution, driving force analysis, dynamic model simulation, social and economic correlation, and ecological effects [13].

Based on an assessment of the changes to the social, economic, and ecological environment of the middle and lower reaches of the Yellow River Basin after the completion of the Xiaolangdi Dam, this paper therefore aims to evaluate the sustainability impacts of the construction of this large-scale water conservancy project. To do this, it provides a quantitative assessment of the social, economic, and ecological impacts in the Yellow River Basin [14]. Based on the interpretation of data in the form of Landsat remote sensing images in 5-year periods from 2000 to 2020, this paper analyzes the temporal change characteristics of each land use type in the middle and lower reaches of the Yellow River Basin by means of a land use dynamic index and land use degree comprehensive comparison method. Combined with correlation analysis, conducted for the period after the Xiaolangdi Dam was operational, the influence of socio-economic development factors on land use change is examined in order to provide a scientific decision-making reference for the rational utilization of land resources, ecological environmental protection, and regional sustainable development in the middle and lower reaches of the Yellow River Basin.

2. Materials and Methods

2.1. Research Area

The Xiaolangdi Dam is located in the last section of the Yellow River Gorge (Figure 1), with a total reservoir capacity of 12.65 billion cubic meters, controlling 90% of the Yellow

River water and nearly 100% of the sediment transport volume. The Xiaolangdi Dam is the only place on the Yellow River below Sanmenxia that can maintain a large storage capacity and is also the only comprehensive large-scale reservoir that can fully undertake the tasks of flood control, water supply, and irrigation. The Xiaolangdi Dam is the first project in China that is fully compliant with international management practices. It was partly financed by a loan from the World Bank. The main project was subject to comprehensive international bidding, and the personnel involved in the construction came from 51 countries and regions around the world. The dam consists of the dam structure, a flood discharge building, and a power diversion system. The preliminary project was started in September 1991 and the first Xiaolangdi power generation unit was connected to the grid in January 2000. The Xiaolangdi Reservoir has an average annual water regulation capacity of 2 billion m^3, which can meet the irrigation and urban water demand in the downstream area, thereby improving the irrigation guarantee rate.

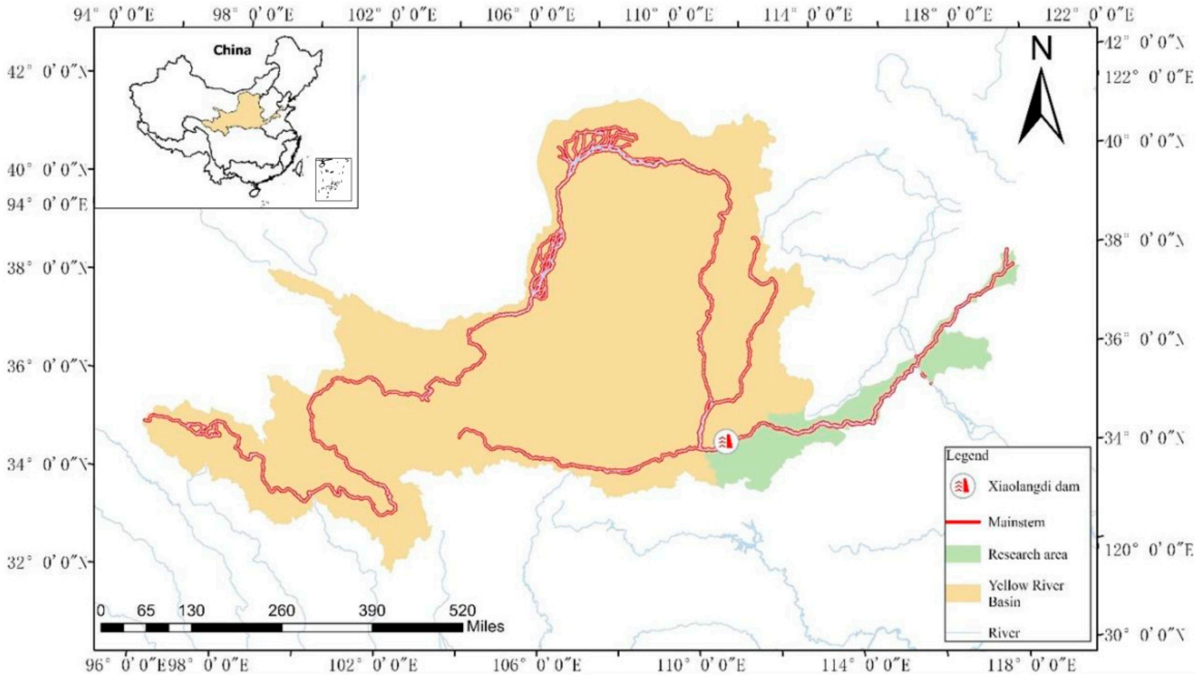

Figure 1. The research area in the Yellow River Basin.

In the ten years before the Xiaolangdi Dam was put into operation (1991~2000), the Yellow River flow was cut off for 901 days, including 226 days in 1997, along an average length of 422 km. After the Xiaolangdi Dam became operational, under the premise that the natural runoff of the Yellow River has decreased by more than 10%, the inflow of the Xiaolangdi reservoir decreased by more than 20%, while the water consumption of the Henan and Shandong provinces in the lower reaches of the Yellow River has increased year by year. The Xiaolangdi Hydraulic project has ensured the continuous flow of the lower reaches of the Yellow River, along with a continuous improvement in the ecological environment, to provide security for social and economic development [15,16]. The beneficiary area has now reached 59,400 km^2.

2.2. Data Resources

The land use type distribution in the research area in 2000, 2005, 2010, 2015, and 2020 was generated using an interpretation of Landsat TM/ETM remote sensing images with a resolution of 1 km × 1 km (Table 1) [17]. The land use types in the research area were divided into 6 primary types: cropland, forest land, grassland, water area, construction land, and unused land. Cropland refers to land where crops are grown, including paddy fields and dry land. The cropland in the research area is mainly dry land. Forest land refers to forested areas comprising trees and shrubs. The forest land in the research area is mainly high-forest. The grassland was divided into three different coverage types: high, medium, and low. The grassland in the research area was mainly high and medium coverage. The water area refers to natural land waters and water conservancy facilities, which, in the research area, is mainly lakes, reservoirs, and canals. The construction land in the research area includes urban and rural residential areas and other industrial, mining, and transportation land. Unused land refers to land that has not yet been used and land that is difficult to use. The unused land is mainly saline–alkali land and marshland.

Table 1. Data resources.

Data Type	Data Resource	Time Resolution	Spatial Resolution	Remarks
Population (person/km^2)	National Earth System Science Data Center	2000, 2005, 2010, 2015, 2020	1 km	Statistical yearbook of Shandong Province and Henan Province
GDP (ten thousand CNY/km^2)	National Earth System Science Data Center	2000, 2005, 2010, 2015, 2020	1 km	Statistical yearbook of Shandong Province and Henan Province
Land use	Resources and Environmental Sciences and Data Center	2000, 2005, 2010, 2015, 2020	1 km	Landsat TM/ETM

Note: The basic data were obtained from the Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/, accessed on 30 June 2023), National Earth System Science Data Center, and the National Science and Technology Infrastructure of China (http://www.geodata.cn, accessed on 30 June 2023).

2.3. Analysis of Land Use Change Rate

The dynamic degree of land use can reflect the land use type change for a certain period of time. The dynamic degree of land use was calculated using the following formula [18]. It reflects the intensity of land use change in the research area.

$$K = \left[\sum_{i=0}^{n} \left(\frac{\Delta S_{i-j}}{S_i} \right) \right] / T \tag{1}$$

In the Formula (1), K represents the dynamic attitude of land use types in T time period, ΔS_{i-j} represents land use type i converted to other land use types in T time period, and S_i represents i's land area in the Initial period. K reflects the type of land use change rate; larger K indicates that, in a certain period within the research area, the change is stronger, and smaller K indicates that land use type change is weaker.

2.4. Comprehensive Index of Land Use

The comprehensive index of land use degree can reflect the level human land use in a certain period. Referring to the comprehensive index analysis method of land use degree proposed by Zhuang Dafang and Liu Jiyuan [19], this paper divided land use types into four levels according to different use modes and assigned values, with the value of unused land designated 1. Forestland, grassland, and water areas are assigned a value of 2, cropland is 3, construction land is 4, and the comprehensive index of land use degree was calculated according to the following formula.

$$La = 100 \times \sum_{i=1}^{n} A_i \times C_i \tag{2}$$

In the Formula (2), La represents the comprehensive index of land use degree, A_i represents the degree grade index of Class i land use, and C_i represents the area proportion of Class i land use. $La \in$ [100, 400]. If the value of La equates to 400, it indicates that the research area is developing in the direction of urban agglomeration; if the value of *La* equates to 100, it indicates that the research area tends to be unutilized or undeveloped.

2.5. Correlation Analysis between Land Use Change and Socio-Economic Indicators

The Pearson correlation coefficient and significant difference analysis between the six land use types in the study area, and the corresponding population and GDP in the same period, were then calculated. The Pearson correlation coefficient can reflect the degree of close correlation between land use type and socio-economic indicators [20]. The correlation coefficient is expressed by r. When $|r| \in [0.8, 1]$, there is a strong correlation between variables. When $|r| \in [0.5, 0.8]$ indicates a moderate correlation between variables. When $|r| \in [0.3, 0.5]$, it indicates a low correlation between variables. When $|r| \in [0, 0.3]$, there is weak or no correlation between the variables. Double-tail test analysis was used to calculate the significance difference using the *p*-value. If the *p*-value is less than 0.05, it indicates that there is a significant correlation between the two variables.

3. Results

3.1. Analysis of the Characteristics of Land Use Change

The data of six types of land use in five periods in the middle and lower reaches of the Yellow River Basin were statistically analyzed, and the results show that cropland was the main type of land use (Table 2), accounting for more than 56% of the total area. The proportion of unused land is the lowest, at less than 1%. The area of cropland decreased in the five periods. The cropland area decreased the most during 2010~2015 and 2015~2020, declining by 383 and 348 km^2, respectively. The area of forestland, grassland, and unused land decreased during 2000~2005 and 2005~2010, and remained basically unchanged during 2010~2015 and 2015~2020. The area of forestland, grassland, and unused land decreased the most between 2005 and 2010, declining by 114, 558 and 162 km^2, respectively. The water area showed an increasing trend in five periods, with a larger increase during 2000–2005 and 2005~2010, and a smaller increase during 2010~2015 and 2015~2020. The area of the construction land showed an increasing trend in five periods with the largest increase of 893 km^2 in 2005~2010. The overall analysis from 2000 to 2020 shows that the area of cropland, forestland, grassland, and unused land in the study area showed a downward trend, with the cropland area showing the largest decline, decreasing by 1113 km^2. The water area and construction land showed an increasing trend, with construction land expanding by 1910 km^2.

Table 2. Area change in land use type in the research area.

Item	Year	Land Use Type					
		Cropland	**Forestland**	**Grassland**	**Water Area**	**Construction Land**	**Unused Land**
Area proportion (%)	2000	58.78	16.29	9.42	3.81	11.07	0.64
	2005	58.45	16.25	8.68	4.49	11.64	0.49
	2010	58.13	16.06	7.74	4.70	13.14	0.22
	2015	57.49	16.06	7.74	4.77	13.73	0.21
	2020	56.90	16.06	7.73	4.81	14.28	0.21
Area change (km^2)	2000–2005	−195	−24	−439	405	341	−88
	2005–2010	−187	−114	−558	128	893	−162
	2010–2015	−383	2	−3	40	347	−3
	2015–2020	−348	0	−4	25	329	−2
	2000–2020	−1113	−136	−1004	598	1910	−255

The cropland in the middle and lower reaches of the Yellow River Basin is mainly distributed in the middle and eastern regions (Figure 2), and the irrigation area of the Yellow River is concentrated and contiguous. Forest land is mainly distributed in the western region, while grassland is mainly distributed in scattered areas in the east and west and shows a gradually decreasing trend. The water area is gradually increasing, mainly along the Yellow River and the estuary area. Urban and rural construction land is mainly located in the urban circle along the middle and lower reaches of the Yellow River, and is gradually expanding. Unused land is gradually decreasing, with the decrease mainly in the salinized land area.

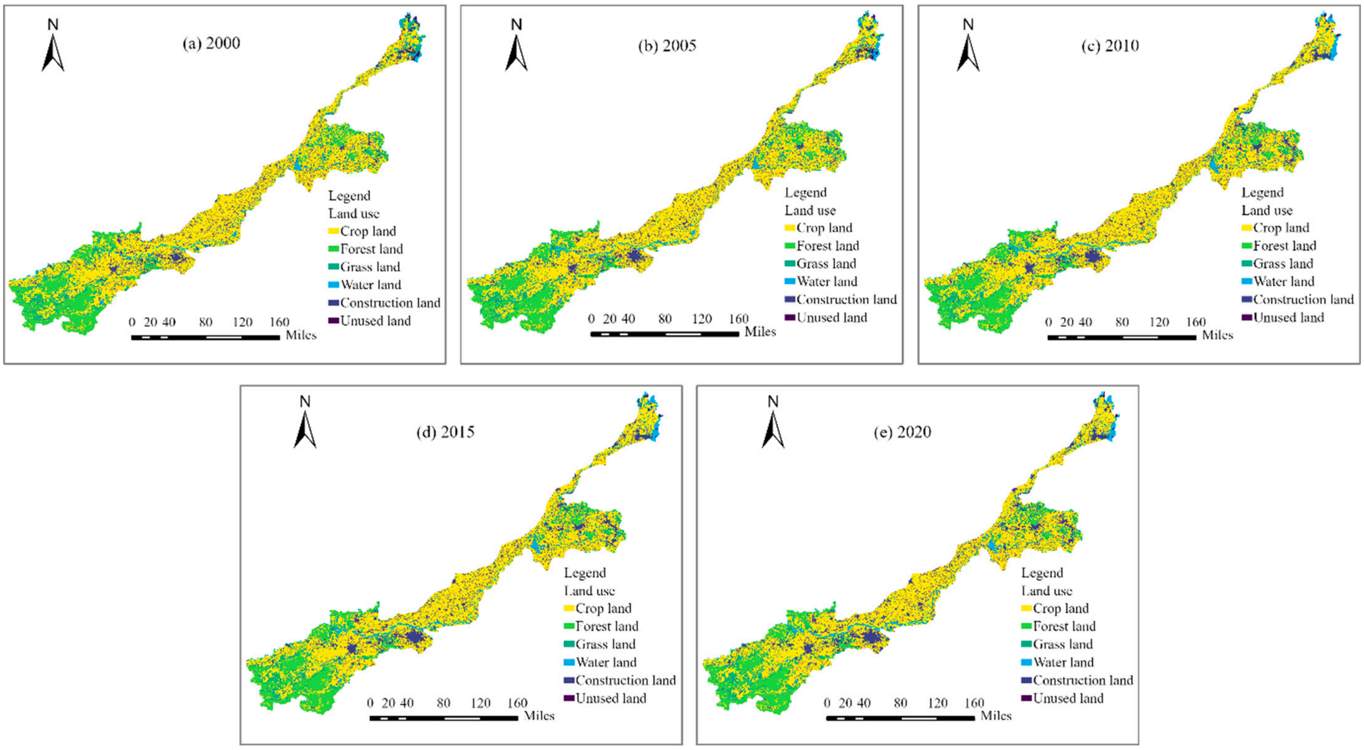

Figure 2. Spatial patterns of land use in research area from 2000 to 2020.

3.2. Time Change Characteristics of Land Use Types

The results of the change and dynamic attitude of land use in different periods of the research area show that the changes in construction land, unused land, water area, and grassland are significant, while forest land is almost unchanged (Table 3). According to the overall analysis from 2000 to 2020, the maximum dynamic degree of land use was during 2005 to 2010 (17.14%), and the second fastest was from 2000 to 2005 (10.98%), indicating that the land use change in these two periods was more drastic. During the period from 2015 to 2020 land use change was relatively stable (1.52%). Overall, the dynamic attitude of land use in the study area showed a decreasing trend, indicating that the land use in the middle and lower reaches of the Yellow River developed in a more stable direction during the five periods studied.

Table 3. Change and dynamic attitude of land use in research area (%).

Period	Cropland	Forestland	Grassland	Water Area	Construction Land	Unused Land	Dynamic Degree of Land Use
2000–2005	−0.11	−0.05	−1.57	3.58	1.04	−4.63	10.98
2005–2010	−0.11	−0.24	−2.16	0.96	2.58	−11.10	17.14
2010–2015	−0.22	0.00	−0.01	0.29	0.89	−0.46	1.88
2015–2020	−0.20	0.00	−0.02	0.18	0.81	−0.31	1.52
2000–2020	−0.16	−0.07	−0.90	1.32	1.45	−3.36	7.26

The comprehensive index of land use in each period from 2000 to 2020 in the research area shows that the comprehensive index of land use in the five periods is between 280 and 285, which is categorized as a medium level and shows a rising trend (Figure 3). This indicates that the research area is developing in the direction of urban settlement development.

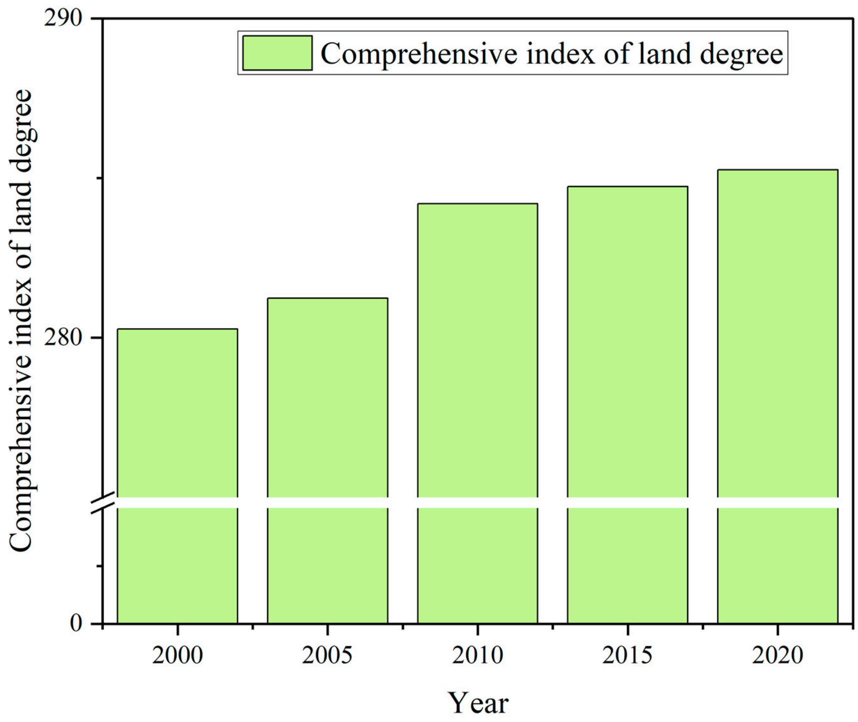

Figure 3. Comprehensive index analysis of land use in the research area.

3.3. Correlation Analysis between Land Use Change and Socio-Economic Indicators

The driving forces of land use change are both natural and human factors. Here, we mainly analyze the relationship between economic society and land use change. As shown in Figure 4, the population and GDP of the study area increased significantly between 2000 and 2020. Compared to 2000, the number of people in the study area increased slightly in 2020, and several densely populated urban patches increased significantly. Compared with 2000, the GDP of the study areas in 2020 had increased significantly. This increase is not only reflected in the densely populated urban patches but also in some areas with previously lower GDP, whose GDP is now close to that of the densely populated urban patches. The change in degree of GDP in the study area is greater than that of population change during 2000~2020, indicating that economic and social indicators are mainly reflected in GDP. As shown in Table 4, from 2000 to 2020, the research area population index increased by 21.13%, and the research area GDP index (yuan/km^2) increased by 903.66%. The increase in GDP index is significantly higher than that of population growth, indicating that the growth of economic and social indicators is mainly reflected in GDP growth, which is consistent with the results in Figure 4.

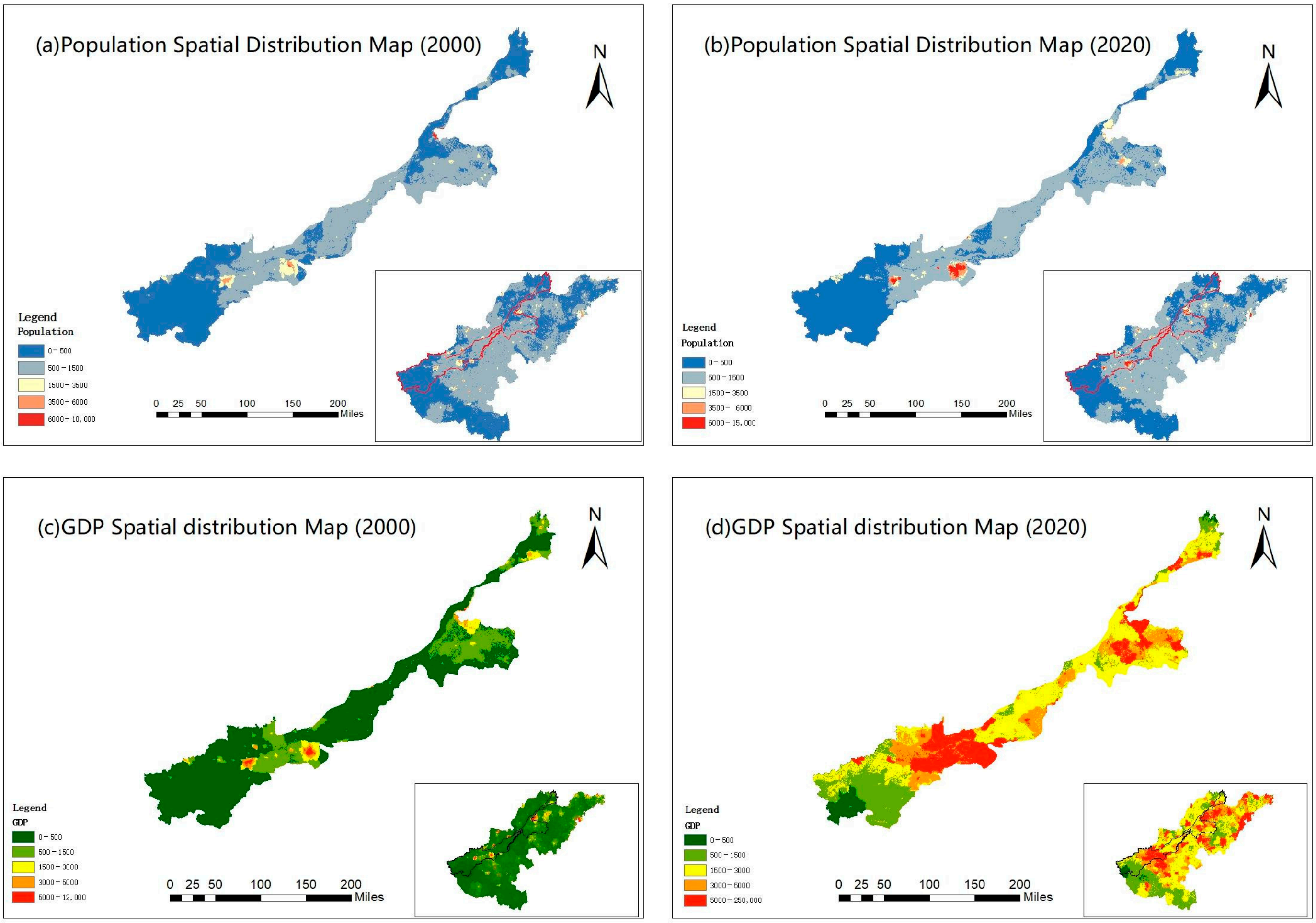

Figure 4. Population and GDP changes from 2000 to 2020.

Table 4. Changes in socio-economic indicators from 2000 to 2020.

Indicators/Year	2000	2020	Growth Rate
Research area population index (person/km^2)	530	642	21.13%
Population index of the province (person/km^2)	553	617	11.57%
Research area GDP index (CNY/km^2)	465	4667	903.66%
GDP index of the province (ten thousand CNY/km^2)	433	3851	789.38%

Figure 5 shows the correlation between socio-economic index factors and different land use types. In the Yellow River Basin's middle and lower reaches, the cropland and unused land area are significantly negatively correlated with socio-economic index factors. In addition, the area of grassland and woodland is negatively correlated with socio-economic index factors, the area of construction land is significantly positively correlated with socio-economic index factors, and the area of water is positively correlated with socio-economic index factors. Among them, the cropland area has a strong correlation with GDP and population, and the correlation coefficient reaches −1.00 and −0.99, respectively. The construction land area has a strong correlation with GDP and population, and the correlation coefficient is 0.96.

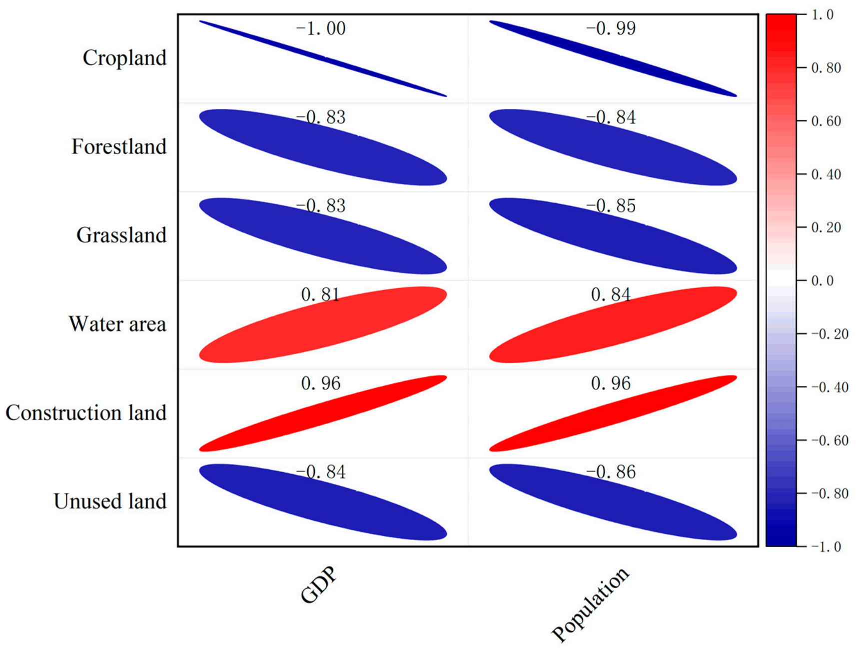

Figure 5. The correlation between socio-economic index factors and different land use types.

4. Discussion

This study shows that cropland, forestland, and construction land are the largest land use types in the middle and lower reaches of the Yellow River Basin from 2000 to 2020, accounting for more than 85% of the total area. Cropland is the largest land use type and it is also the most important means of production in the middle and lower reaches of the Yellow River basin. This study points out that cropland, forestland, grassland, and unused land in the middle and lower reaches of the Yellow River Basin show a continuous decreasing trend from 2000 to 2020. Water area and construction land are the main transfer types of other land types.

From 2000 to 2005, the water area increased. This may be due to the commissioning of the Xiaolangdi Dam. Due to the operation of the Xiaolangdi Dam from 2000 onwards, the uninterrupted flow of the Yellow River has been ensured, thereby maintaining the ecological water supply needs of the middle and lower reaches of the Yellow River and playing a crucial role in the ecological protection of the Yellow River Basin [21,22]. Using this water supply, the Henan and Shandong provinces have successively established the Henan Yellow River Wetland National Nature Reserve and the Shandong Yellow River Delta National Nature Reserve. As a result, the water area represented by wetlands and reservoirs has continued to expand. From 2000 to 2020, the water area within the study area increased by 598 km^2.

Urban agglomeration along the Yellow River, primarily in the two provincial capitals of Zhengzhou and Jinan, occurred rapidly during the study period and the construction land area continued to increase. There was a total increase of 1910 km^2 during this period. Due to the increase in construction land and human activities, the area of grassland and cropland has declined. With the continuous increase in population, the unused land along the Yellow River, mainly saline–alkali land, was also effectively utilized after treatment. From 2010 to 2020, the comprehensive dynamic attitude of land use fell below 2% every five years, the land use change in the basin tended to be stable, and the change in each land use type decreased year by year.

Grassland decreased significantly during 2000~2010, and slowed down during 2010~2020. Since 1999, China has carried out ecological improvement projects to return cropland to forests and grasslands [23]. A total of 142 thousand km^2 of cropland has been returned to forests and grasslands by 25 provinces, autonomous regions, and municipalities directly under the central government and the Xinjiang Production and Construction Corps.

At the same time, 207 thousand km^2 of barren mountains and wasteland have undergone afforestation, thus alleviating and improving the deteriorating ecological environment and ecosystem functions [24]. For the reasons above, the declining trend of grassland in the study areas from 2010 to 2020 has slowed down. However, the results of this study show that grassland in the study area still declined by 997 km^2 from 2000 to 2010, and have not recovered effectively yet. Therefore, the changes in grassland areas in the study areas are not only been influenced by the implementation of policies, but also by social and economic development and human activities. Previous studies have pointed out that urbanization rate, transportation development, and economic development level are important driving factors affecting the change in cropland and grassland areas [25–27]. In this study, the grassland area in the middle and lower reaches of the Yellow River Basin showed a significant negative correlation with population and GDP. Therefore, the rapid development of population and social economy is also the main factor leading to the decline of grassland in the study area.

Construction land is the land use type with the largest single land use change rate in the middle and lower reaches of the Yellow River, and its distribution area shows an upward trend and is significantly positively correlated with population and GDP. Previous studies have pointed out that social and economic development level and industrialization levels are driving factors for urban and rural construction land expansion [28,29]. In the past 20 years, the economy of the middle and lower reaches of the Yellow River has been developing continuously, and population and GDP have shown an increasing trend, indicating that socio-economic development and the urbanization rate are the main driving forces leading to the expansion of construction land in the study area. From 2005 to 2020, the total area converted into construction land is 1910 km^2, of which cropland and grassland are the largest. Studies have shown that the expansion of construction land in the Yellow River Basin is at the expense of cropland [30] but grassland is also being converted to this land use. According to this study, the reduction in grassland area caused by the expansion of construction land in the Yellow River Basin should not be ignored.

Economic development has a certain impact on ecology, such as the reduction in grassland, but the implementation of some policies, such as returning farmland to forest, can improve environmental damage and achieve sustainable development. In addition, soil and water conservation and afforestation during dam construction can have a positive impact on the environment.

5. Conclusions

This study aimed to quantitatively assess the sustainability impacts of the Xiaolangdi Dam. The results show that, after Xiaolangdi became operational, it injected new vitality into the Yellow River, the mother river of China, to ensure that it does not stop flowing and promote the social and economic development of the basin. It has had some positive effects on social and economic conditions in Shandong, Henan, and other provinces in the middle and lower reaches of the Yellow River. Urban agglomeration along the Yellow River has witnessed substantial growth, and the population siphon effect is significant. The growth rates of GDP and population in the Yellow River Basin of Shandong and Henan Province are higher than the provincial average. GDP and population growth has driven increases in land use change, construction land, and water area, and decreases in unused land, cropland, and grassland. The land use type changed significantly in the ten years after the dam became operational and, thereafter, tended to be stable. Critically, in terms of overall sustainability, ecological protection has been enhanced, with the area of forestland being almost unchanged and the ecological flow of the water having increased, thereby allowing the development of wetland nature reserves. This study, therefore, provides a basis for further research examining how dam construction can improve ecological conditions, alongside the socio-economic environment, in river basins in order to support sustainable development. Such research is also necessary to strengthen the protection of cultivated land in the Yellow River basin. Finally, Xiaolangdi should also continue to play its role in ecological protection.

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