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Impact of Social and Economic Development on Sediment Load of the Yellow River

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Abstract: Approximately 90% of the sediment yield of the Yellow River is derived from the Loess Plateau. In this paper, the Loess Plateau was used as the research object. To investigate the influence of economic and social development on reducing sediment load of the Yellow River, a mathematical method was employed with hydrological and sediment data from three hydrological stations (Toudaoguai and Sanmenxia at the Yellow River, and Ganguyi at the Yan River) as well as per capita GDP data from the Yan River basin. The results showed that the reduction in runoff in the reaches between the Toudaoguai and Sanmenxia stations accounted for 39.3% of the decrease in the sediment load of the Yellow River, and the other 60.7% of the decrease may have resulted from economic and social development. Using the Yan River basin as an example, there was an inverse relationship between per capita GDP and sediment delivery during the period from 1984 to 2018. Grey relational analysis revealed a relatively high relation between the sediment load of the Yan River and the number of rural laborers transferred from the area, the afforestation area, and the tertiary industry value of Yan'an city. Thus, economic development and social transformation are highly related to sediment delivery in the basin, which may result in a decrease in sediment delivery to some extent.

Keywords: sediment yield; economic development; social transformation; GDP; Yellow River; Yan River

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1. Introduction

Since ancient times, the survival and development of human beings have been closely related to rivers; even now, most of the big cities in the world are still located along rivers [1]. The interactions between river systems and social and economic development of the human world are quite complicated [2]. In recent decades, as social and economic development and human activities have intensified, their impacts on river systems have become more and more obvious [3–6]. Previous studies have revealed that human activities, such as the construction of water conservancy facilities and land-use changes, have led to great changes in the underlying surface conditions of the river basins, altering runoff and sediment processes dramatically [7–9]. In particular, a significant decline in sediment load has been observed in many large river systems [10–14]. This produces problems, such as delta retreat and nutrient input reduction to aquatic and riparian ecosystems [15,16], which has become a focus of attention worldwide [17,18]. Therefore, to maintain the management of the water basin sustainably, it is necessary to evaluate the impacts of different socioeconomic indicators on river sediment load.

The Yellow River is the second largest river in China and has once the most sediment transport worldwide. For example, the average annual sediment load at the Sanmenxia station (the controlled watershed area of which accounts for 91.5% of the Yellow River basin area) was approximately 1.52 billion tons per year between 1919 to 1953 [19]. In recent decades, with the improvement of social and economic activities, the area of the Yellow River basin has been transformed from great development to ecological protection. Various soil and water conservation measures and policies for returning farmland to forests have been adopted by the government in China [18,20]. As a result of these measures, sediment load in the Yellow River has been reduced drastically [21]. Numerous investigations of the causes of the sediment load reduction of the Yellow River have been conducted, but most of the current studies mainly focus on changes in water and sediment regime and soil and water conservation. The social and economic factors have received much less attention [2].

Social and economic conditions affect sediment load by controlling human activities [2]. For example, through socioeconomic development, an increase in government investment in returning farmland to forests, and improvements of systems of soil and water conservation, resulting in land-use changes, the sediment yield in the basin has declined [22]. In this paper, based on water and sediment data at the Toudaoguai and Sanmenxia stations and precipitation data, the causes of the runoff and sediment reduction of the Yellow River were investigated. Moreover, to discuss the influence of economic and social development on reducing the sediment load of the Yellow River, a typical tributary of the Yellow River—the Yan River basin—was selected as an example. We collected and analyzed eighteen indicators of social and economic development in the Yan River basin, and clarified relations between socioeconomic indicators and sediment load. It should be noticed that the society in China transformed from a planned economy to a socialist market economy in the period from 1984 to 2003, and individual labor was the main role of farmers during this time. After 2004, the development of the socialist market economy system matured, and Chinese society essentially became an industrial society. Thus, this paper compares the sediment load of the Yellow River between the agricultural society period (1958–1983) and the industrial society period (2004–2018) to investigate the impact of economic and social development on the sediment load of the Yellow River.

One of the outcomes of this work is an ability to better understand how economic development and social transformation affect river sediment load, so as to provide references for the sustainable development of the river basin.

2. Regional Setting

The Yellow River flows through nine provinces (districts) into the Bohai Sea in Kenli County, Shandong Province. The basin area is 795,000 km^2, and the total length of the river is 5464 km. The Yellow River basin is located at 32–42° N and 96–119° E. Three terraces are distributed from west to east based on changes in altitude. The Loess Plateau is located in the middle part, with an altitude between 1000 and 2000 m.

The water and sediment regimes of the Yellow River show obvious regional differences. Most of the water discharge comes from the channel reach located upstream of Lanzhou, and most of the sediment load comes from the channel reach located between Toudaoguan and Longmen as the river flows through the Loess Plateau. Figure 1 shows the area that contributes a large amount of course sediment. Due to the heavy sediment load and riverbank constraints, the lower Yellow River has high sediment deposits and is well known as a suspended river.

The Loess Plateau mainly had gullies instead of vegetation before 1983, while the soil was highly erodible. The precipitation is low, with one or two strong storms generally occurring in spring or autumn. The Yan River is a typical distributary of the Yellow River, which is located on the Loess Plateau and mainly belongs to the Yan'an administrative region (Figure 1). The area of the Yan River drainage basin is 7725 km^2, which contributes approximately 1% of the total drainage area of the Yellow River. Before 1983, Chinese society had a planned economy, in which approximately 90% of the population in the Yan River drainage basin were farmers, and rural collective labor was their main job. The average per capita GDP in Yan'an was 351 yuan/person (54 $US/person), and the society was a typical agricultural society.

During the summer of 1983, researchers spent a month performing observations in the Yan River basin. From this research we know that crops there were grown on the hillslope at 20 degrees. After storms the surface of the hillslopes was severely eroded, and high sediment-laden flow was created at the tributary.

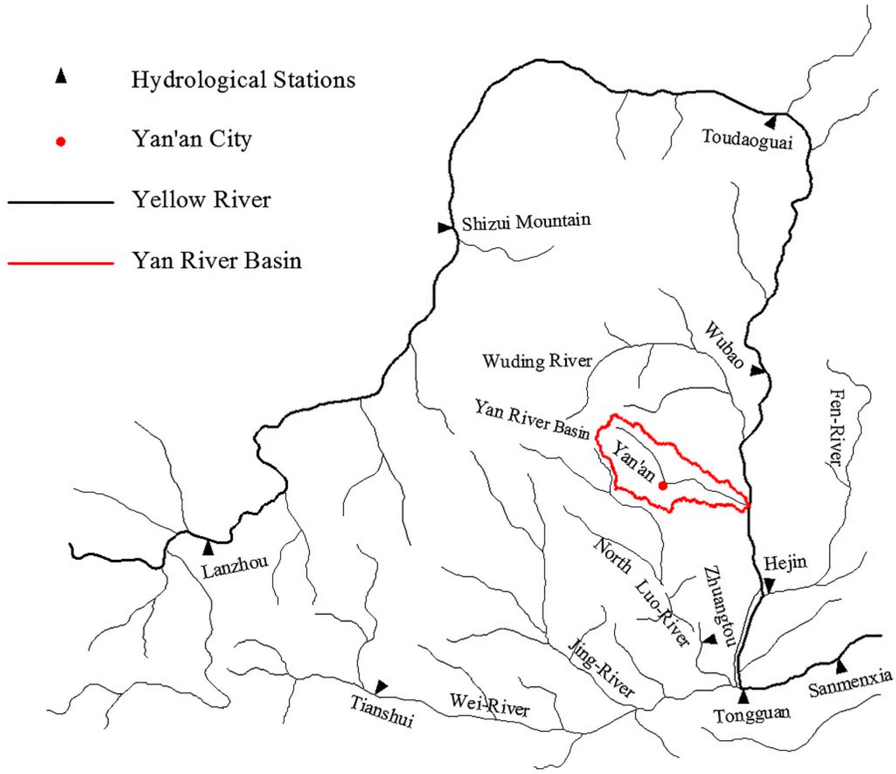

Figure 1. Drainage area of the Yellow River.

3. Data and Methods

3.1. Data

Annual runoff and sediment load data at stations of Toudaoguai, Sanmenxia, and Ganguyi (1958–2018), and annual precipitation and water consumption between the Toudaoguai and Sanmenxia stations, were provided by the Yellow River Conservancy Commission. Eighteen indicators of social and economic development in the Yan River basin, including GDP and per capita GDP; primary, secondary, and tertiary industry value; urban and rural per capita disposable income; resident population; urbanization rate; rural labor transfer; regional, industrial, and agricultural irrigation water consumption; cultivated land area, afforestation area, controlled soil and water loss area; and precipitation and maximum single-day rainfall were collected from the Yan'an and Shannxi statistical yearbooks (http://fzbz.yanan.gov.cn/, http://dfz.shaanxi.gov.cn/ accessed on 16 June 2021). The timings of various indicator measurements were not completely consistent due to incomplete statistics in the early period of study. Indicators were generally collected from 2000 to 2018, except for the urbanization rate and the number of rural labor transfers, which were collected from 2010 to 2018 and from 2006 to 2018, respectively.

3.2. Methods

A mathematical method called a linear-regression analysis was employed with hydrological and sediment data from three hydrological stations (Toudaoguai and Sanmenxia at the Yellow River, and Ganguyi at the Yan River), as well as per capita GDP data from the

Yan River basin. Linear-regression is a model to establish a linear correlation between two sets of data, so as to predict values of one set from another [23].

Additionally, grey relation analysis (GRA) was used to investigate the relevancies between water and sediment regime and eighteen socioeconomic indicators in the Yan River basin. The GRA calls upon Deng's grey system theory [24], which is a multi-factor statistical analysis method for determining the correlation grade between factors [25]. In this study, the four steps of calculation are the same as in the study of Li et al. [26]. We classified the eighteen indicators of social and economic development in the Yan River basin into three types: economic, social, and eco-environment, according to their characteristics.

4. Results

4.1. Changes in Runoff of the Yellow River and Its Causes

A decreasing trend in runoff at Sanmenxia station during 1958–2018 can be observed in Figure 2. As shown, the average annual runoff decreased 41.5%, from 408.3 × 10^8 m^3/yr during 1958–1983 to 238.7 × 10^8 m^3/yr during 2004–2018.

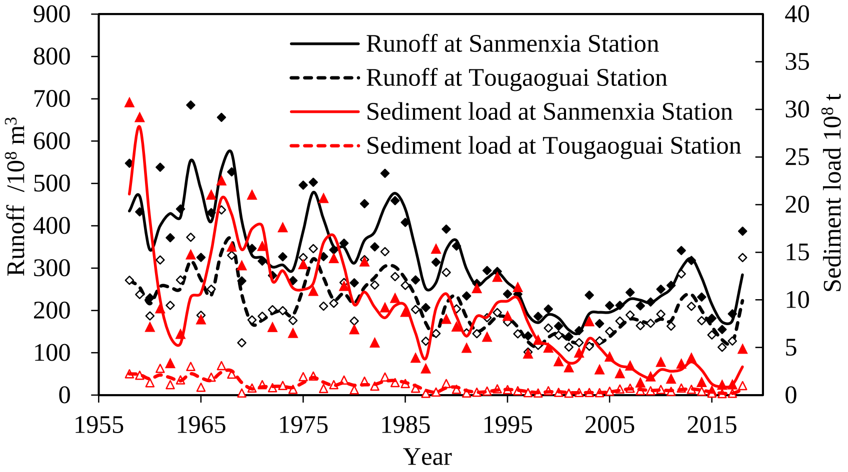

Figure 2. Annual variations in the flow and sediment regime at Sanmenxia and Toudaoguai station of the Yellow River from 1958 to 2018.

Taking the Toudaoguai station as the entrance control station, the reasons for the decrease in runoff in reaches of the Yellow River between the Toudaoguai and Sanmenxia stations (hereafter referred to as the Tou-San reach) were analyzed. The average annual runoff at the Toudaoguai station decreased by 67.7%, from 253.9 × 10^8 m^3/yr during 1958–1983 to 180.7 × 10^8 m^3/yr during 2004–2018. At the Sanmenxia station, the average annual runoff decreased by 82.0%. The reduction in runoff at Sanmenxia station was larger than that at the Toudaoguai station, implying that the decrease in runoff at the Sanmenxia station was not only due to the decrease in runoff at the entrance control station. There were other contributing factors, such as changes in precipitation or water consumption in the Tou-San reach.

As shown in Figure 3, the average annual precipitation during the two periods of 1958–1983 and 2004–2018 was generally the same, with values of 520.0 mm/yr and 518.1 mm/yr, respectively. However, the average annual runoff during 1958–1983 and 2004–2018 had large differences, with values of 154.4 × 10^8 m^3/yr and 58.1 × 10^8 m^3/yr, respectively.

Taking into account the values from 1958–1983, in which the annual runoff was 154.7 × 10^8 m^3/yr and the average annual precipitation was 520.0 mm/yr, we can assume that if conditions were to have remained the same the corresponding runoff values for 2004–2018 should be 153.6 × 10^8 m^3/yr, as the average annual precipitation was 518.1 mm/yr. However, the actual reduction in runoff from 1958–1983 to 2004–2018 was

96.3×10^8 m^3/yr. Thus, the decrease in precipitation explained only 1.2% of the runoff decrease, while other factors contributed 98.8% of the decrease in runoff.

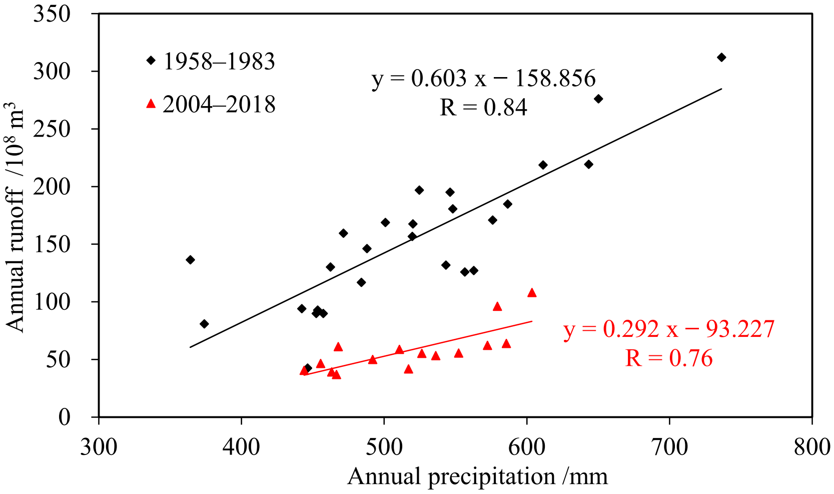

Figure 3. Relationship between precipitation and runoff in the Yellow River basin between the Toudaoguai and Sanmenxia stations.

Water consumption in the Yellow River basin between the Toudaoguai and Sanmenxia stations obviously increased (Figure 4). The average annual consumption increased from 37.09×10^8 m^3/yr during 1958–1983 to 54.24×10^8 m^3/yr during 2004–2018. The relationship between water consumption and runoff in the Yellow River basin between the Toudaoguai and Sanmenxia stations is shown in Figure 5, and nonlinear regression was performed during the two periods. Even though the fitting precision was low, using the same method above for runoff reduction analysis, we estimated that increased water consumption resulted in a 54.3% decrease in the runoff. Therefore, the increase in water consumption may be the main factor affecting runoff reduction in the Yellow River basin between the Toudaoguai and Sanmenxia stations.

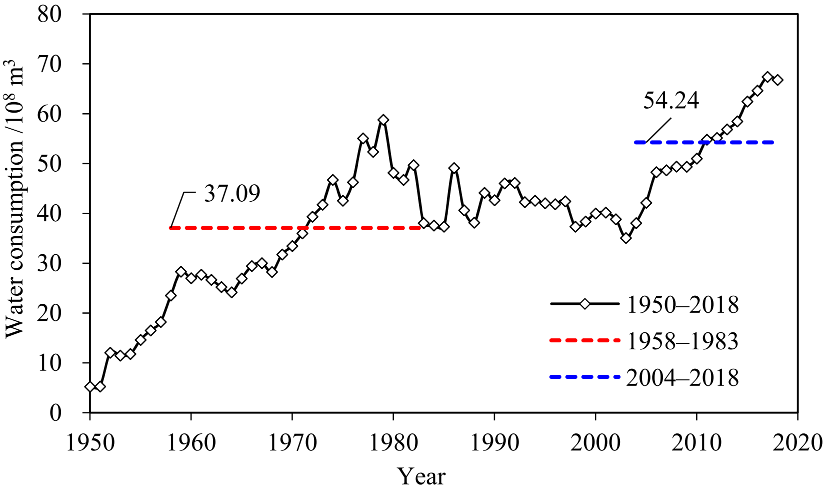

Figure 4. Water consumption in the Yellow River basin between the Toudaoguai and Sanmenxia stations.

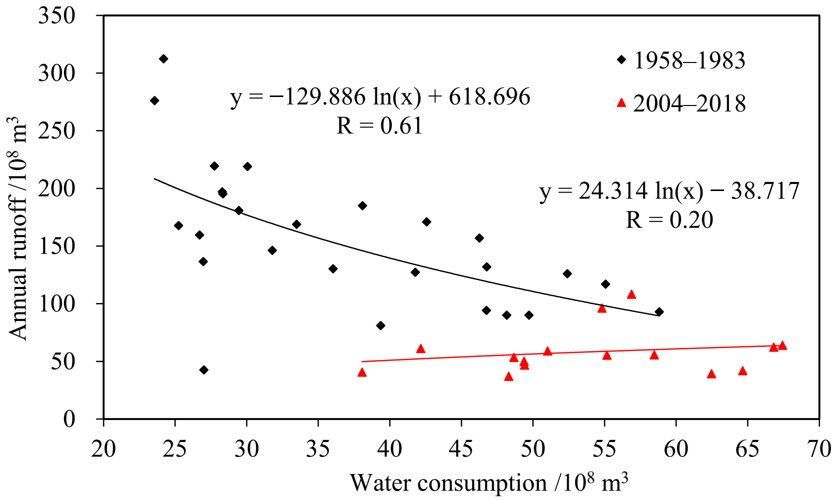

Figure 5. Relationship between water consumption and runoff in the Yellow River basin between the Toudaoguai and Sanmenxia stations.

4.2. Changes in Sediment Load of the Yellow River and Its Causes

There is also an obvious reduction trend in sediment load at the Sanmenxia station during 1958–2018. The average annual sediment load decreased 82.0%, from 13.73×10^8 t/yr in the period of 1958–1983 to 2.48×10^8 t/yr in the period of 2004–2018. The reduction in sediment load was greater than that of runoff (54.3%).

The reduction in runoff will weaken the flow dynamics of sediment transport. Relationship between annual runoff and sediment transport can be seen in Figure 6. Using the same method estimated that the reduction in runoff explained 39.3% of the decrease in sediment load, implying that 60.7% of the decrease in sediment load resulted from other factors.

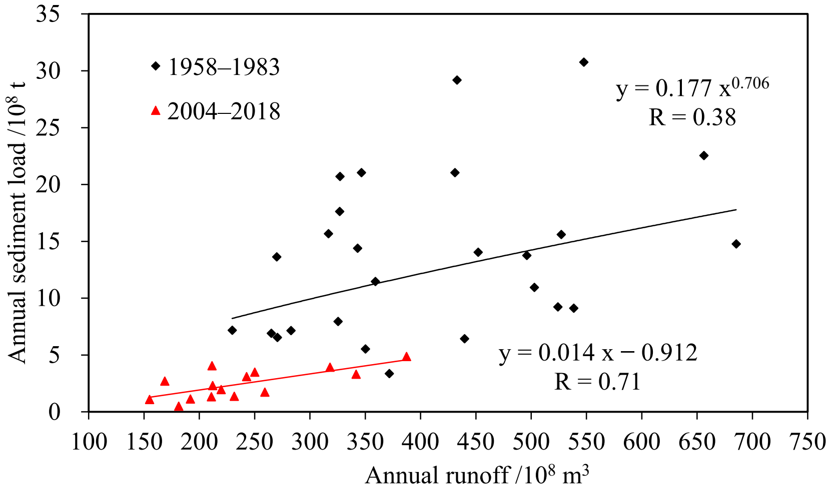

Figure 6. Relationship between annual runoff and sediment transport at the Sanmenxia station during two periods: 1958–1983 and 2004–2018.

4.3. Relationship Between per Capita GDP and Sediment Load in the Yan River Basin

Locating at the Loess Plateau, the Yan River basin is one of the main sediment-producing areas, which belongs to Yan'an City (Figure 1). As shown in Table 1, the annual average sediment load of the Yan River basin accounted for 3.71% and 2.82% of the total sediment transport in the Yellow River in 1958–1983 and 2004–2018, respectively. However, the average annual runoff of the Yan River basin was only 0.55% and 0.61% of the total runoff in the Yellow River, respectively. As an important tributary of the Yellow River, the Yan River basin accounts for only 1% of the Yellow River basin area. Hence, an analysis of the water and sediment changes in the Yan River is essential for the investigation of the reduced sediment in the Yellow River.

Table 1. The runoff and sediment transport proportions.

Period	**Ganguyi Station in the Yan River**		**Sanmenxia Station in the Yellow River**		**Proportion**	
	Runoff 10^8 **m**^{3}**/yr**	**Sediment Load** 10^8 **t/yr**	**Runoff** 10^8 **m**^{3}**/yr**	**Sediment Load** 10^8 **t/yr**	**Runoff %**	**Sediment Load %**
1958–1983	2.25	0.51	408.3	13.73	0.55	3.71
2004–2018	1.45	0.07	238.7	2.48	0.61	2.82

Similar to the Yellow River, the runoff and sediment load in the Yan River were reduced, decreasing by 35.6% and 86.3%, respectively. The average runoff and sediment load values were 2.25×10^8 m^3/yr and 0.51×10^8 t/yr during 1958–1983 and 1.45×10^8 m^3/yr and 0.07×10^8 t/yr during 2004–2018, respectively (Table 1). The average annual precipitation increased by 3.9%, from 532.5 mm/yr in 1958–1983 to 554.0 mm/yr in 2004–2018 in the Yan River basin. The average annual precipitation increased, while the annual runoff declined, indicating that the decrease in runoff in the Yan River basin may be mainly due to the socioeconomic development-induced increase in water consumption. The relationship between the indicator of social and economic development—the per capita GDP and the sediment load at the control hydrological station in the Yan River basin was established, as displayed in Figure 7, an inverse relationship could be observed over the past 25 years. As shown, the sediment load decreased while the per capita GDP increased, and the sediment reduction was notable early on, declining steadily to a relatively low level by the end of the period.

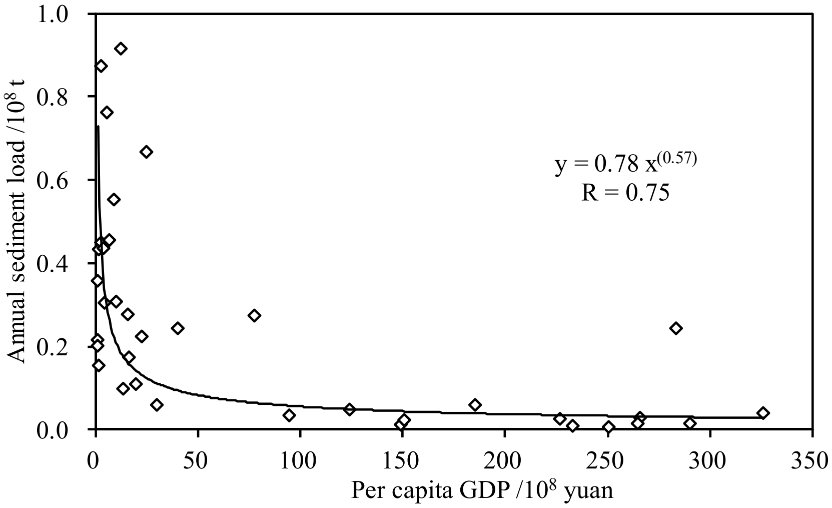

Figure 7. Curve of per capita GDP and sediment transport in the Yan River basin from 1984 to 2018.

4.4. Analysis of Causes of Changes in Water and Sediment Regimes in the Yan River Basin

The relationships between the water and sediment regime of the Yan River and these eighteen indicators (Figure 8) were calculated using the grey relational analysis model, as shown in Table 2. The results showed that the relationships between runoff and eco-environmental indicators are high, ranging from 0.650 to 0.739. Relatively high values were observed between runoff and social indicators, with values from 0.448–0.707. The relevancies between runoff and economic indicators were generally at the same level, with an average value of 0.586. The relevancies between sediment load and economic and eco-environmental indicators had no significant difference, with ranges of 0.529–0.610 and 0.509–0.629, respectively. Except for the relevance between the sediment load and the number of rural laborers transferred, which was 0.732, the relevancies between the sediment load and other social indicators were generally low, ranging from 0.405 to 0.535.

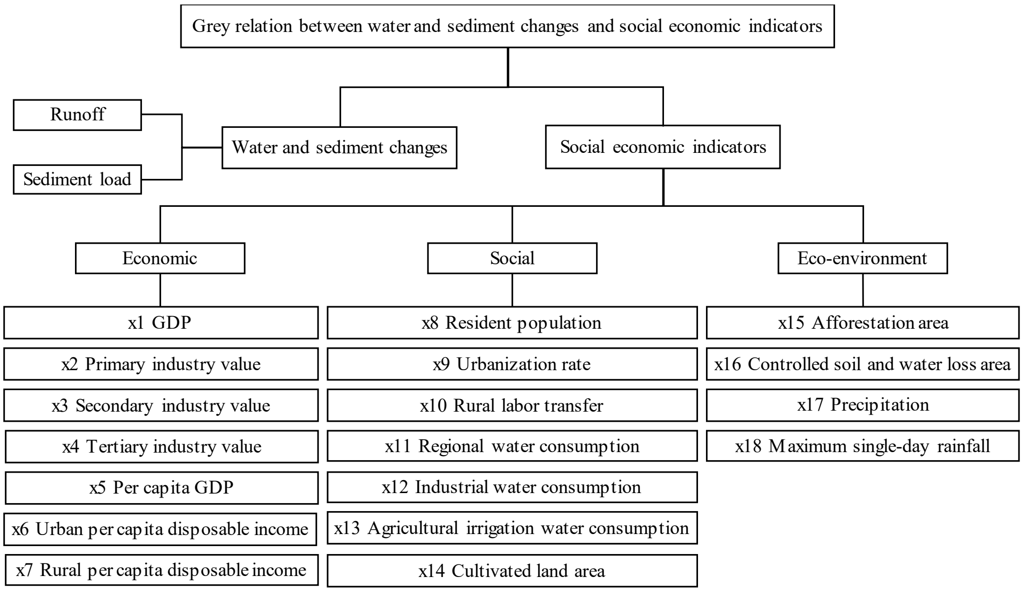

Figure 8. Grey relational diagram between water and sediment changes and socioeconomic indicators.

Table 2. Relevancies between water and sediment regime and socioeconomic indicators in the Yan River basin.

Economic	**x1**	**x2**	**x3**	**x4**	**x5**	**x6**	**x7**
Runoff	0.584	0.585	0.576	0.591	0.588	0.581	0.595
Sediment load	0.546	0.581	0.529	0.610	0.541	0.558	0.574
Social	**x8**	**x9**	**x10**	**x11**	**x12**	**x13**	**x14**
Runoff	0.448	0.610	0.707	0.522	0.560	0.500	0.451
Sediment load	0.405	0.535	0.723	0.447	0.501	0.443	0.413
Eco-Environment	**x15**	**x16**	**x17**	**x18**			
Runoff	0.739	0.728	0.650	0.704			
Sediment load	0.629	0.566	0.509	0.550			

5. Discussion

5.1. Social and Economic Factors Affecting Sediment Yield of the Yellow River

As shown in the analysis above, 39.3% of the decrease in sediment load resulted from the decrease in the runoff. The other 60.7% has been considered, by many Chinese scholars, to be the main effect of water and soil conservation [9,10,12,20]. For example, during the second half of the 20th century, high-intensity and high-standard water and soil conservation treatments were carried out in the mid-western Oklahoma basin. The sediment load of the main tributaries was reduced from 760 mg/km^2 before the treatment (1943–1948) to 108 mg/km^2 after the treatment (2004–2007), and this reduction was mainly caused by water and soil conservation and land-use management [27].

Soil erosion control of the Loess Plateau began in the 1950s, and water and soil conservation began to change from disorderly management to comprehensive management and planning in the 1960s. At the end of the 1970s, it was proposed that soil and water loss control should focus on sandy and coarse sand-producing areas. However, the amount of sediment reduction was limited due to the hysteresis effect of the water and soil conservation measures. The average annual sediment discharge of the Sanmenxia station in the period from 1958 to 1983 was 13.73 × 10^8 t/yr, which was less than the value of 15.32 × 10^8 t/yr in 1924–1953. At the beginning of the 1980s, a comprehensive management strategy began, with small watersheds as units, in which water conservation measures played a significant role. By the end of 2002, a technical system for the construction of the ditch dam system with "the tributaries as the skeleton, the small watershed as the unit, the backbone dams and the small and medium silt dams matched" was formed [28–30]. Therefore, the average annual sediment discharge of the Sanmenxia station in the Yellow River decreased to 7.25×10^8 t/yr in 1984–2003.

After 1997, the central and local governments of the Loess Plateau carried out the conversion of cropland to forest, ecological construction and ecological restoration projects, and paid subsidies to farmers for forest conservation [20,31]. These measures played an important role in curbing sediment erosion and reducing sediment sources. For example, the land-use patterns in the Wuding River basin and Yan River basin changed significantly by 2013. Sloped farmland has mostly been restored to natural conditions, vegetation is in a recovery stage, and there are a small number of terrace fields that cultivate greenhouse vegetables. In 2013, the agricultural acreage was less than one-third that of 30 years ago. Chinese society was a typical industrial society after 2004, and the per capita GDP of the Yan River basin in 2018 was 68,940 yuan/person (10,641 $US/person), which was 196 times the levels seen in 1983. Due to the relatively low level of agricultural production, most of the rural labor force have been actively transferred to cities and are engaged in local construction, the service industry, or the oil and coal industry. The structure of rural energy consumption is also changing, previously relying mainly on firewood but now mostly using electricity, coal, natural gas, and methane. It can be said that the farmers helped with the spontaneous closure of the forest and the restoration of vegetation. These changes, e.g., the transfer of the rural labor force and changes in the structure of rural energy consumption, enhance water and soil conservation. Therefore, compared to 1958–1983, the average annual sediment load at the Ganguyi station in the Yan River decreased by 86.3% during 2004–2018.

In summary, the reduction in runoff was mainly due to increasing water consumption and socioeconomic development. Over the past 35 years, regarding the development of the national and local social economies, the government has invested in water and soil conservation projects and subsidized farmers to increase the intensity of closing hillsides and increasing afforestation. The transfer of the rural labor force and the change in the structure of rural energy consumption were also related to economic development and social transformation. Thus, the reduction of sediment load may be highly related to socioeconomic development. To establish the quantitative relationship between the indicators of social and economic development, the per capita GDP was chosen as a characteristic quantity, and a typical tributary of the Yellow River was selected as an example as discussed below.

5.2. The Impact of Social and Economic Development on Sediment Load in a Typical Tributary of the Yellow River

The rapid social and economic development of districts along the river was based on the natural resources of the Yellow River. In turn, social and economic development inevitably had a certain impact on the water and sediment regimes of the Yellow River.

Taking the Yan River basin as an example, an obvious inverse relationship can be observed between sediment load and the per capita GDP over the past 25 years. This is consistent with the conclusion of Zhong et al. (2021), that socioeconomic factors in the Yan River basin promote its sustainable development [2]. More specifically, making a horizontal comparison between the relevancies of runoff and sediment load and three different categories of indicators, the results showed that the highest relevance between runoff and the three categories of indicators was 0.595 for the rural per capita disposable income, 0.707 for the number of rural laborers transferred, and 0.739 for the afforestation area. Similarly, the highest relevance between sediment load and the three categories of indicators was 0.610 for the tertiary industry value, 0.723 for the number of rural laborers transferred, and 0.629 for the afforestation area. Runoff was most related to afforestation area, while sediment load was most related to the number of rural laborers transferred.

Similar conclusions have been drawn in precious studies [2,32–34], for example, Zhong et al. (2021) revealed that increased urbanization rates resulting from population migration led to reductions in sediment load, and cultivated land area is positively correlated with sediment load [2].

In summary, socioeconomic development has greatly affected the water and sediment regime of the Yan River. After 2000, the conversion of cultivated land to forests in Yan'an city was basically completed according to the plan. Afforestation on barren mountains and the closure of mountains for afforestation became more important factors affecting the reduction of sediment yield in the Yan River basin. The transfer of the rural labor force and the increase in tertiary industry value indicate that the improvement of people's production and lifestyle affected the changes in sediment yield to a certain extent.

6. Conclusions

(1). The average annual runoff and sediment load at Sanmenxia station on the Yellow River decreased by 41.5% and 82.0%, respectively in 2004–2018, compared with those in 1958–1983. The decrease in runoff was mainly caused by an increase in water consumption. Approximately 39.3% of the sediment reduction was due to the decrease in runoff, and the remaining 66.4% was attributed to other factors.

(2). During the periods 1958–1983 and 2004–2018, the average annual runoff and sediment load in the Yan River decreased by 35.6% and 86.3%, respectively. An inverse relation between the per capita GDP and the sediment load can be observed over the past 25 years in the Yan River basin, and the sediment reduction was notable at an early stage, steadily declining to a relatively low level by the end of the period.

(3). The sediment load in the Yan River was highly related to the transfer of rural laborers, the afforestation area, and the tertiary industry value during 2000–2018, indicating that human activities can both increase sediment and reduce sediment. Thus, in recent decades, the development of the social economy in the river basin decreased the sediment yield to some extent.

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