hydrology

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Factors Affecting Runoff and Sediment Load Changes in the Wuding River Basin from 1960 to 2020

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Abstract: To investigate changes in runoff and sediment load in the Wuding River basin under the combined influence of climate change and human activities, trends were analyzed from 1960 to 2020, and the contribution rate of climate change and human activities was calculated. It was observed that the runoff and sediment load Mann–Kendall test value ranges at eight gauging stations were −7.42 to −3.88 and −9.28 to −3.34, respectively, indicating a significant decreasing trend in both. During the period of 1970–2000, the contribution of human activities to the reduction in runoff and sediment load was 69.9% and 75.3%, respectively. However, the impact of human activities intensified after 2001 due to the implementation of the policy of returning farmland to forests in the Wuding River basin, which contributed to 118.4% and 114.5% of the reduction in runoff and sediment load, respectively. Check dam and reservoir construction, reforestation, water diversion, and other human activities were all important factors in runoff and sediment load reduction. In particular, the total sediment retention by reservoirs in the Wuding River basin was approximately 879 million tons until 2010, and the total sediment retention by check dams was approximately 2747 million t until 2017. This study can provide support for the utilization of water resources and the construction of ecological civilization in the Wuding River basin, and can also provide a reference for the study of water and sediment changes in other basins.

Keywords: Wuding River basin; runoff; sediment load; soil and water conservation; check dam

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1. Introduction

The runoff and sediment yield in a river basin are the result of the combined action of climate conditions and the underlying surface. Climate variables, such as rainfall, are the primary factors affecting runoff. Moreover, human activities, such as water and soil conservation measures, have changed the underlying surface conditions of river basins, consequently affecting the mechanisms of runoff and sediment load. With climate change and the intensification of human activities, the runoff and sediment load of many rivers around the world have changed, which has led to a series of problems [1–3]. Therefore, a hot topic is distinguishing the contribution rate of climate change and human activities to the variations in runoff and sediment load in a basin [4–6]. In order to clarify the relationship between climate change and the trend in runoff and sediment load, a large number of studies have been successfully carried out in the Yellow River, Yanhe River, Manawatu River, and Mekong River, among others, using the sequence test and regression model methods [7–9].

Wuding River, which flows through the Loess Plateau of China, is a representative tributary of the coarse silt and silty area in the middle reaches of the Yellow River, and is a sensitive area to climate change. Soil erosion has been a very serious issue here since ancient times. In order to improve the ecological environment, large-scale ecological construction projects, such as soil and water conservation, have been implemented in the Wuding River basin since the 1950s. In particular, the construction of check dams in the 1970s and the implementation of the policy of returning cultivated land to forests in 1999 have had a significant impact on the changes in runoff and sediment load in the basin. With increases in the governance scale, the underlying surface conditions have changed, and the runoff and sediment load have also been greatly affected, generating widespread concern. The analysis of a hydrometeorological series from 1955 to 2012 showed that precipitation and evaporation in the Wuding River basin generally decreased over this period, although this trend was not significant [10]. Compared with the 1960s, the annual average runoff and sediment load of the basin from 2010 to 2020 decreased by 41.5% and 90%, respectively.

Presently, there are different views on the variation in runoff and sediment load, and the contribution of various influencing factors, in the Wuding River basin. Although there is much research on the influencing factors and contributions of runoff and sediment load change, the research on the applicability of various methods and the comparison of calculation results is still insufficient. In addition, human activities are the main reason for the reduction in sediment transport, but it is difficult to distinguish the impacts of reservoir construction and warping dam construction. Based on variation analysis results, this study qualitatively assessed the impact of climate change and human activities in the Wuding River basin using methods such as the Mann–Kendall test, a comparison method of cumulative slope change rate, and the hydrological method. Including human activities in the basin, such as the construction of check dams, implementation of the policy of returning farmland to forests, reservoir construction, and diversion irrigation, the main influencing factors and their contributions to the variation in runoff and sediment load were then analyzed. This study is not only helpful to identify the main factors that cause runoff and sediment changes, but also has a profound understanding of the role of human activities. In addition, this study aimed to support water resource management of the Wuding River basin, and provided a reference for the runoff and sediment load change analysis of other basins.

2. Study Area and Data

2.1. Study Area

The Wuding River is a tributary of the Yellow River, located in the north of Shaanxi Province, China, with a total length of 491 km and a drainage area of 30,260 km^2. The Wuding River basin is located in the north China continental arid and semi-arid climate zones, with an average annual temperature of 7.9–11.2 °C and annual precipitation of 350–500 mm. The annual average runoff and sediment load were 10.87 m^3 and 94.6615 million tons, respectively, from 1956 to 2020. The tributaries and eight gauging stations in the Wuding River basin are shown in Figure 1. In particular, Baijiachuan gauging station is the most downstream gauging station at the outlet of the Wuding River basin, with a controlled drainage area of 29,662 km^2, accounting for 98% of the total drainage area.

2.2. Data

Data from the eight gauging stations: Baijiachuan, Hanjiashuan, Hengshan, Danshi, Zhao Shiyao, Dingjiagou, Lijiahe, and Suide, were selected for the analysis of water-sand changes in runoff and sand transport in the Wuding River basin (Figure 1). The monitoring data at each gauging station from 1957 to 2020 were obtained from the Hydrological Yearbook of the Yellow River basin.

The annual rainfall was calculated using the weighted average of the data of 29 rainfall stations in the Wuding River basin, including Zizhou, Hanjiamao, and Hengshan [11]. The weight is the ratio of the area of the Thiessen polygon controlled by each rainfall station to the total area of the Wuding River basin.

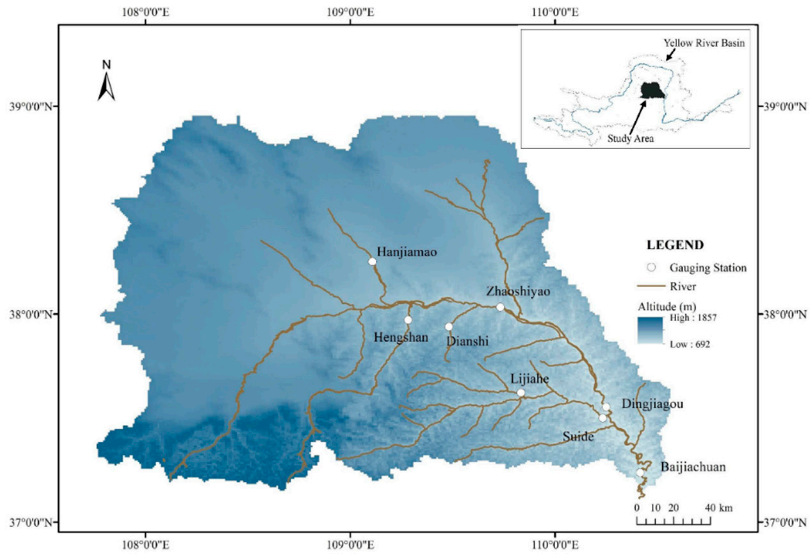

Figure 1. Tributaries and gauging stations in the Wuding River basin.

The Thiessen polygon method, which was proposed by Dutch climatologist A·H·Thiessen, calculates the average rainfall based on the rainfall of monitoring stations with a discrete distribution, and this method uses area weighting to solve the error caused by the uneven distribution of monitoring stations. First, all adjacent monitoring stations in the study area are connected into a triangle. Second, the vertical bisectors on each side of these triangles are made, so that several vertical bisectors around each monitoring station form a polygon. Third, the rainfall of the only monitoring station contained in each polygon represents the average rainfall in this polygon area. The calculation formula of average rainfall in the study area is as follows:

$$\overline{P} = \frac{f_1 x_1 + f_2 x_2 + \ldots + f_n x_n}{f_1 + f_2 + \ldots + f_n} \quad (1)$$

where $\overline{P}$ is the average rainfall of the study area, mm; x_i is the rainfall of the i-th monitoring station, mm; f_i is the area of the polygon where the i-th monitoring station is located, km^2; n is the number of monitoring stations in the study area. Data relating to water and soil conservation projects and water conservancy projects in the Wuding River basin were mainly derived from the bulletin of first national census for water or relevant research papers.

3. Methods

There are many research methods currently available for the hydrological response assessment of climate change [12], among which the hydrological trend analysis method, represented by the hydrological method and the double accumulation curve method, is the most widely used.

3.1. Mann–Kendall Trend Test

The quantification of the contribution rate of climate change and human activities to runoff or sediment variation requires a combination of methods such as a trend analysis and the catastrophe test. In this study, the Mann–Kendall (M–K) trend test was used to analyze runoff and sediment load. It is a nonparametric test method that does not require samples to follow a certain distribution, and is suitable for the trending testing of nonnormal distribution data [13].

For a given time series $X(x_1, x_2, \ldots \ldots, x_\mathrm{n})$, the statistic Z is defined as

$$Z = \sum_{i=1}^{n} \sum_{j=i+1}^{n-1} sgn\left(x_j - x_i\right) \quad (2)$$

where n is the number of samples. Once n is greater than 8, Z values will follow an approximate normal distribution. Then, the Mann–Kendall M is given by

$$M = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}} \quad (k = 1, 2, \cdots n) \tag{3}$$

where $E(S_k) = k(k+1)/4$ and $Var(S_k) = k(k+1)(2k+5)/72$. The critical value can be obtained by consulting the normal distribution table under a certain confidence level. When $|M| > 1.96$, it shows an increasing or decreasing tendency with a confidence level of 95% during a particular period of time.

3.2. Double Mass Curve Analysis

Double mass curve analysis is a common method to make a time series analysis, which mainly uses the characteristics of the curve to analyze the change in the hydrological quantity. It is assumed that the relationship between the cumulative value of hydrological variables and the other variables (such as time or accumulation hydrological variable) is expressed by the following functions [14]:

$$W = f(x) \tag{4}$$

The first-order derivative and second-order derivative are:

$$W' = dW/dx \tag{5}$$

$$W'' = d^2W/dx^2 \tag{6}$$

The first-order derivative (W') represents the rate of change in the hydrological accumulation and the other variable. Under normal circumstances, when the hydrological variable accumulation curve is a straight line ($W'' \approx 0$), the variable values will change without the deviating system, and if the accumulation curve deflects up ($W'' > 0$) or down ($W'' < 0$) at some time, there is an increase or decrease trend for the hydrological variable.

3.3. Comparison Method of Slope Change Rate of Accumulation

The comparison method of slope change rate of accumulation analyzes the attribution of runoff and sediment load changes by comparing the slope of the cumulative curve before and after the abrupt change point. Principles of the method are as follows [15]. If the runoff is only affected by rainfall, the slopes of the cumulative curve of rainfall and runoff with time should vary in the same ratio. That is, the slope change rate of the cumulative curve of runoff and time should be equal to that of the cumulative curve of rainfall and time during the same period. We postulate that the total contribution of all influencing factors of runoff is defined as 1.0. Then, the ratio of the slope change of the cumulative curve of rainfall and time to that of the cumulative curve of runoff and time is the contribution ratio of rainfall to runoff change.

This method first requires analysis of the trends and abruption of a series of annual rainfall, runoff, and sediment load. Each series is divided into two periods: before mutation (base period) and after mutation (research period). Then, the double accumulation curves between annual rainfall (runoff or sediment load) and time are drawn. Q_a and Q_b are the slopes of the linear fitting trend line between the accumulated annual runoff and time. P_a and P_b are the slopes of the linear fitting trend line between the accumulated annual rainfall and time. S_a and S_b are the slopes of the linear fitting trend line between the accumulated annual sediment load and time. The subscripts a and b indicate the period before and after the mutation point, respectively. Therefore, the calculation formula of the slope change rate of the cumulative curve is as follows:

$$R_Q = 100 \times (Q_a - Q_b)/Q_b \tag{7}$$

$$R_P = 100 \times (P_a - P_b)/P_b \quad (8)$$

$$R_s = 100 \times (S_a - S_b)/S_b \quad (9)$$

where R_Q is the slope change rate of cumulative runoff, %; R_P is the slope change rate of cumulative rainfall, %; R_s is the slope change rate of cumulative sediment load, %.

The contribution rates of annual rainfall and human activities to the changes in runoff or sediment load were calculated by the following formula:

$$C_P = 100 \times R_P/R_Q = 100 \times (P_a/P_b - 1)/(Q_a/Q_b - 1) \quad (10)$$

$$C_H = 100 - C_P \quad (11)$$

where C_p is the contribution rate of precipitation, %; C_H is the contribution rate of human activities, %.

3.4. Hydrological Method

The hydrological method statistically analyzes the variation in runoff and sediment load. It mainly distinguishes the contribution of rainfall or human activities to water or sediment by analyzing the mechanism of rainfall-runoff and rainfall-sediment yield. The hydrologic method assumes that if the underlying surface conditions of watershed changes, the runoff and sediment load will also change, even if the rainfall remains unchanged. In this method, it is necessary to establish the linear regression equation of rainfall and runoff (or sediment load) in the base period. By substituting the rainfall data in the research period into the regression equation of rainfall and runoff (or sediment load) in the base period, the calculated annual runoff (or sediment load) can be obtained. The difference in the calculated values between the study period and base period is the influence of precipitation, and the difference between the calculated values and the measured values in the study period is the influence of human activities.

In the base period and study period, the multi-year average rainfall is P_1 and P_2, respectively, and the multi-year average runoff is Q_1 and Q_2, respectively, while $\Delta = Q_2 - Q_1$. The regression equation of annual rainfall (P_a) and annual runoff (Q_a) used in the base period is:

$$Q_a = kP_a + c \quad (12)$$

where k and c are regression coefficients.

The calculation results are Q'_1 and Q'_2 by substituting P_1 and P_2 into Equation (12), respectively. Then, the contributions of precipitation (ΔP) and human activities (ΔH) are:

$$\Delta_P = Q'_2 - Q'_1 \quad (13)$$

$$\Delta_H = \Delta - \Delta_P \quad (14)$$

The contribution rates of annual rainfall and human activities to the changes in runoff were calculated by the following formula:

$$C_P = 100 \times \frac{\Delta_P}{\Delta} = \frac{Q'_2 - Q'_1}{Q_2 - Q_1} \quad (15)$$

$$C_H = 100 - C_P \quad (16)$$

The contribution rate of climate change and human activities to sediment load was also calculated using the above methods.

4. Results

4.1. Runoff and Sediment Load Variation

4.1.1. Runoff Variation

The runoff at the eight gauging stations in the Wuding River Basin showed a decreasing trend from 1960 to 2020, and the M–K test values varied from −7.42 to −3.88 (Table 1 and Figure 2). In particular, the M–K test values at the Suide, Zhaoshiyao, and Baijiachuan gauging stations were −3.88, −7.42, and −6.79, respectively.

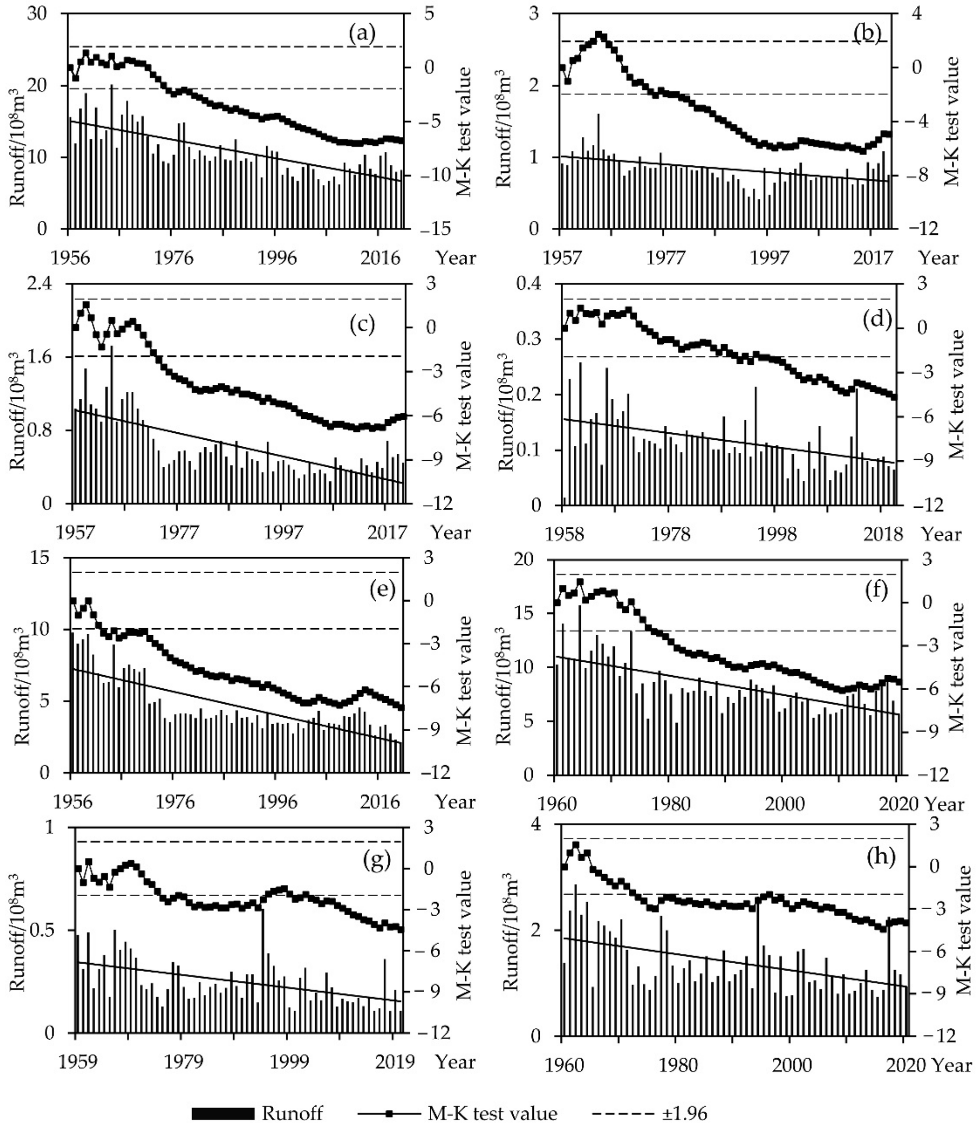

Figure 2. Variations in runoff and M–K test values in the Wuding River basin. (**a**) Baijianchuan gauging station; (**b**) Hanjiamao gauging station; (**c**) Hengshan gauging station; (**d**) Dianshi gauging station; (**e**) Zhaoshiyao gauging station; (**f**) Dingjiagou gauging station; (**g**) Lijiahe gauging station; (**h**) Suide gauging station.

Table 1. Runoff values and variation trends (M–K test values) at the eight gauging stations in the Wuding River basin.

Hydrologic Station		**Baijia Chuan**	**Hanjia Mao**	**Heng Shan**	**Dian Shi**	**Zhaoshi Yao**	**Dingjia Gou**	**Lijia He**	**Sui De**
Drainage area (10^4 m^3)		2.962	0.254	0.241	0.033	1.532	2.342	0.081	0.389
Annual runoff/10^8 m^3	1960s	15.21	1.101	1.1520	0.1638	7.172	11.930	0.3647	2.047
	1970s	12.10	0.9012	0.5960	0.1252	4.604	9.354	0.2475	1.477
	1980s	10.36	0.8138	0.5440	0.1197	4.002	7.475	0.2175	1.230
	1990s	9.34	0.6292	0.4634	0.1185	3.520	7.590	0.2866	1.382
	2000s	7.54	0.7589	0.3612	0.0776	3.570	6.374	0.2021	1.158
	2010–2020	8.89	0.7975	0.4549	0.0930	3.335	7.207	0.1629	1.094
	Average value	10.87	0.8392	0.6223	0.1161	4.665	8.282	0.2492	1.395
M-K test	Value	−6.79	−4.94	−6.06	−4.67	−7.42	−5.35	−4.44	−3.88
	Trend	Decrease							

The runoff in the Wuding River Basin decreased from 1960 to 2020. Compared with the 1960s, the average runoff at the eight gauging stations during the period of 2010–2020 decreased by 28–61%. In addition, the annual runoff at each gauging station generally decreased before 2010; however, the annual runoff at some gauging stations increased slightly after 2010. For example, the multi-year average runoff at the Baijiachuan gauging station was 1.087 billion m^3, which gradually decreased from 1.521 billion m^3 in the 1960s to 7.54 m^3 in the 2000s, and then recovered to 889 million m^3 in the period of 2010–2020.

4.1.2. Sediment Load Variation

Table 2 and Figure 3 reveal that the sediment load at the eight gauging stations in the Wuding River basin decreased from 1960 to 2020, and the M–K test values varied from −9.28 to −3.34. In particular, the M–K test values at the Suide, Zhaoshiyao, and Baijiachuan gauging stations were −3.99, −9.28, and −6.36, respectively.

The sediment load in the Wuding River basin decreased significantly and continuously from 1960 to 2020. Compared with the 1960s, the average sediment load at the eight gauging stations during the period of 2010–2020 decreased by 85–99%. For example, the multi-year average sediment load at the Baijiachuan station was 94.66 million tons, which gradually decreased from 186.65 million tons in 1960 to 36.17 million tons in the 2000s, and then continued to decrease to 18.95 million tons between 2010 and 2020.

Table 2. Sediment load values and variation trends (M–K test values) at the eight gauging stations in the Wuding River basin.

Hydrologic Station		**Baijia Chuan**	**Hanjia Mao**	**Heng Shan**	**Dian Shi**	**Zhaoshi Yao**	**Dingjia Gou**	**Lijia He**	**Sui De**
Annual runoff/10^8 m^3	1960s	18,665	49.76	1432	536.68	2672	8019.8	1218.5	6100
	1970s	11,597	22.2	365.94	209.05	1111	4249.8	475.76	3851
	1980s	5270	15.30	209.11	98.49	641.75	1515.9	296.82	1961
	1990s	8406	5.727	231.03	117.59	227.8	2251.9	637.00	3609
	2000s	3617	4.394	55.65	98.49	50.13	1054.25	366.45	2092
	2010–2020	1895	4.694	6.43	42.18	49.85	369.09	151.50	942.9
	Average value	9466	18.02	486. 5	189.1	1088	2822	537.6	3057
M-K test	Value	−6.36	−7.63	−7.39	−4.95	−9.28	−6.67	−3.34	−3.99
	Trend	Decrease							

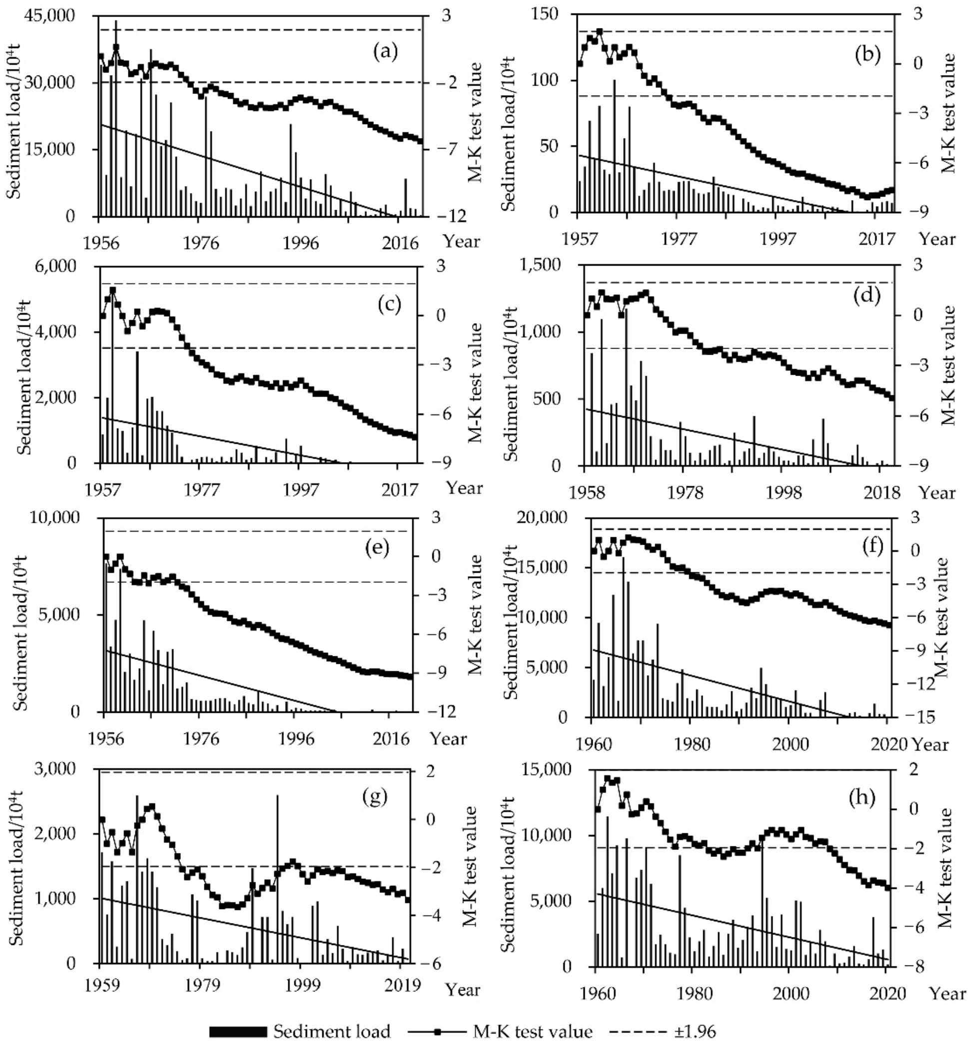

Figure 3. Variations in the sediment load and M–K test values in the Wuding River basin. (**a**) Baijianchuan gauging station; (**b**) Hanjiamao gauging station; (**c**) Hengshan gauging station; (**d**) Dianshi gauging station; (**e**) Zhaoshiyao gauging station; (**f**) Dingjiagou gauging station; (**g**) Lijiahe gauging station; (**h**) Suide gauging station.

4.1.3. Variation in the Runoff and Sediment Load Relationship

The double accumulation curve of runoff and sediment load showed a significant turning point in water and sediment characteristic variations in a basin, that is, the slope of the cumulative curve changed significantly. The double accumulation relationship curves of runoff and sediment load showed an obvious upward convex shape (Figure 4), which indicated that the reduction in sediment load was far greater than that of runoff in the Wuding River basin, and that the sediment concentration of the river was also reduced significantly.

In addition, the double cumulative curves of the eight gauging stations all changed between 1970 and 2007. In 1970, large-scale water and soil conservation measures, such as silt dam construction, were implemented, which led to changes in the water and sediment relationship in the basin. After 2007, the runoff was greater than the sediment load with increasing rainfall, which caused the double accumulation curve to deflect downward again (Figure 4a–d,f–h).

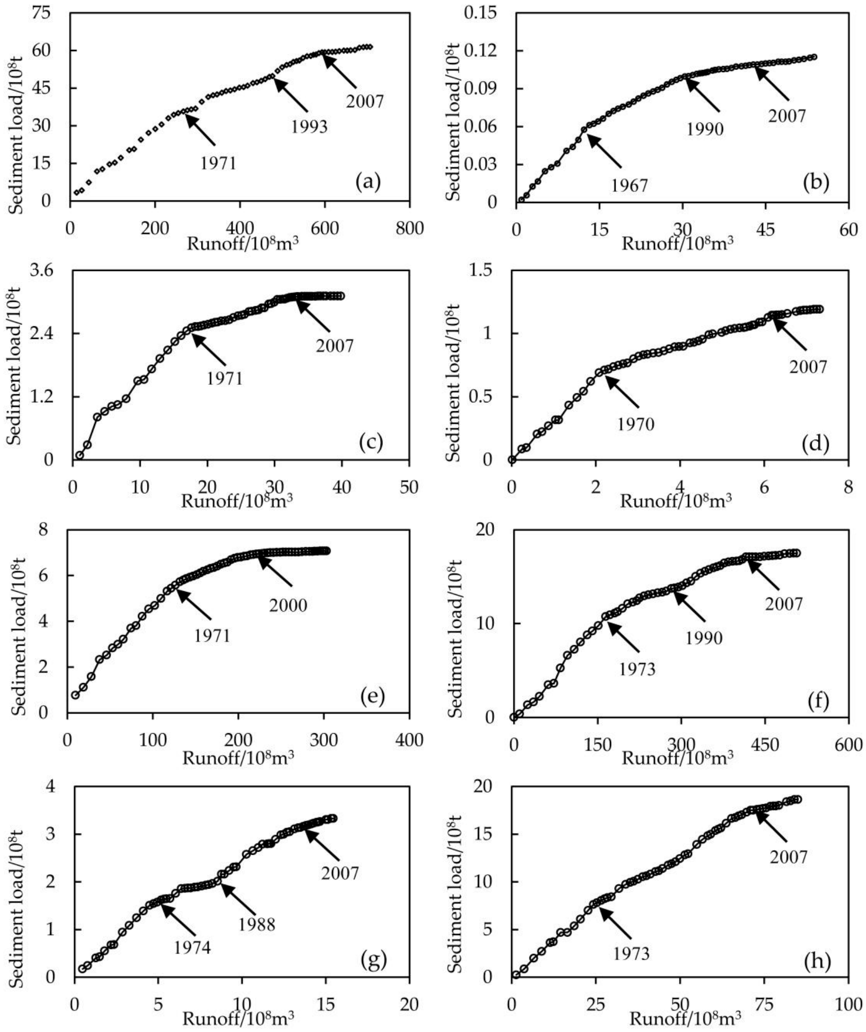

Figure 4. Double cumulative curve of runoff and sediment discharge in the Wuding River basin. (**a**) Baijianchuan gauging station; (**b**) Hanjiamao gauging station; (**c**) Hengshan gauging station; (**d**) Dianshi gauging station; (**e**) Zhaoshiyao gauging station; (**f**) Dingjiagou gauging station; (**g**) Lijiahe Gauging station; (**h**) Suide gauging station.

4.2. Impact of Climate Change

Climate change can affect runoff and sediment load processes in many ways, among which precipitation change is one of the most direct influencing factors. It is known that evaporation in the Wuding River basin over the last 60 years has not decreased significantly [16]. Therefore, this study only considered the rainfall and ignored evapotranspiration when investigating the impact of climate change on changes in runoff and sediment load.

4.2.1. Contribution Rate Calculated by the Cumulative Curve Method

The contribution rate of climate change and human activities to the variation in runoff and sediment load was analyzed using hydrological data of the Baijiachuan gauging station and rainfall data of the Wuding River basin. As previously described, the runoff and sediment load of the Wuding River basin decreased significantly. According to the abrupt change point, the data series of rainfall, runoff, and sediment load could be divided into three periods: base period: 1957–1969; study periods: 1970–2000 and 2001–2020. The double cumulative curves and linear regression curves of runoff, rainfall, and sediment load in the base period and study period were then drawn against year (Figure 5). Compared with the base period, the slope of the linear regression curve reduced in the study period. The runoff and sediment load in the Wuding River basin were analyzed using Equations (1)–(5), and the calculation results are shown in Table 3.

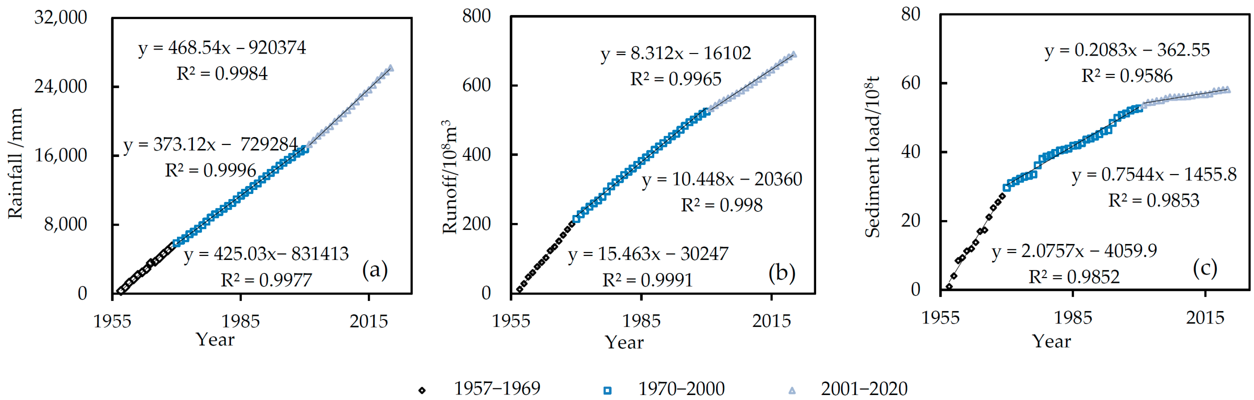

Figure 5. Double cumulative curves of rainfall, runoff, and sediment load over time in the Wuding River basin. (**a**) rainfall over time; (**b**) runoff over time; (**c**) sediment load over time.

Table 3. Contribution rate of climate change and human activities in the Wuding River basin during the study period calculated by the cumulative curve method.

Period		**Rainfall**		**Runoff**		**Sediment Load**		**The Impact of Climate Change**		**The Impact of Human Activity**	
		P_a **or** P_b	R_P	Q_a **or** Q_b	R_R	S_a **or** S_b	R_s	**Runoff**	**Sediment Load**	**Runoff**	**Sediment Load**
Base period	1957–1969	425.03	/	15.463	/	2.0757	/	/	/		
Study period	1970–2000	373.12	−12.21	10.45	−32.43	0.754	−63.67	37.7%	19.2%	62.3%	80.8%
	2001–2020	468.54	10.24	8.321	−46.19	0.208	−89.96	−22.2%	−11.4%	122.2%	111.4%

Human activities were the main reason for the decrease in runoff and sediment load in the Wuding River basin. The contribution of human activities to the changes in runoff and sediment load was greater than that of climate change (Table 2). Moreover, the contribution of human activities to sediment load reduction was significantly greater than its contribution to runoff reduction. During 1970–2000, the contribution rate of rainfall to runoff and sediment load was 37.7% and 19.2%, respectively, and the contribution rate of human activities was 62.3% and 80.8%, respectively. The contribution rate of human activities then increased to 122.2% and 111.4%, respectively, from 2001 to 2020.

4.2.2. Contribution Rate Calculated by the Hydrologic Method

The linear regression equations of rainfall and runoff, and rainfall and sediment load, in the base period were constructed and combined with the hydro-meteorological data of the Wuding River basin, as shown in Figure 6. The correlation coefficients of the rainfall and runoff regression curve, and the rainfall and sediment load, in the base period were 0.86 and 0.50, respectively (Figure 6). The correlation between rainfall and runoff was stronger than that between rainfall and sediment load, which was mainly because rainfall can directly form runoff. The impacts of climate change and human activities on the variation in runoff (or sediment load) in the Wuding River basin were then distinguished quantitatively according to the linear regression equation; the calculation results are shown in Table 4.

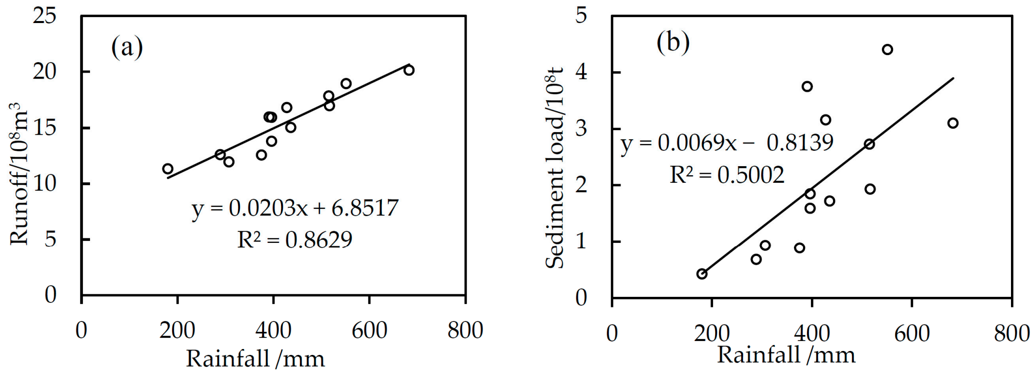

Figure 6. Regression curve of rainfall and runoff (sediment load) of the Wuding River basin in the base period (1957–1969). (**a**) rainfall and runoff; (**b**) rainfall and sediment load.

4.3. Sediment Reduction by Soil and Water Conservation Measures

The water and soil loss area was 16,159 km^2, accounting for 76.5% of the total area of the Wuding River basin, and the average annual erosion modulus was 8000 t/km^2·a. Since the 1950s, soil and water loss prevention measures have been implemented in the Wuding River basin (Table 1). The development of soil and water conservation in the basin (1950–2020) can be divided into three stages: 1. period of preliminary development (1950–1969); 2. period of rapid development (1970–1999); 3. period of stable development (2000–2020). There were few water and soil loss control measures in the first period; the area of soil and water conservation measures was 2153 km^2, accounting for 9.4% of the soil erosion area in the Wuding River basin until 1969. The implementation of water and soil conservation measures increased continuously after 1970, and the Wuding River basin was listed as a national key area for water and soil conservation in 1982 to standardize the management of environmental governance. The area of soil and water conservation was 8364 km^2, accounting for 36.4% of the soil erosion area in the basin until 1996. Specifically, the area of returning farmland to forests and grassland was 67,3400 km^2, the terrace area was 96,600 km^2, and the number of check dams and reservoirs with a storage capacity of more than 1 million m^3 was 11,710 and 74, respectively. The ecological environment of the Wuding River basin has been improved significantly under the policy of reverting farmland to forests since 1999. The accumulated area of soil and water conservation was 12,996 km^2 until 2018, and the control rate of water and soil loss reached 50.93%.

Long-term soil erosion control has an important impact on runoff and sediment load in the Wuding River basin. The contribution rates of soil and water conservation measures to the reduction in runoff and sediment load in the Wuding River basin were 20.78% and 47.26%, respectively [17]. In particular, the effect of soil and water conservation on sediment yield reduction was more obvious during extreme rainfall. For example, the contribution rate of soil and water conservation measures to sediment reduction reached 79% in the Chabagou watershed of the Wuding River during a rainstorm flood on 26 July 2017. Specifically, the sediment retention by gully engineering measures (such as check dams and reservoirs) accounted for 57.7% of the total sediment reduction, while forests and grassland, terraces, and other measures on the slope accounted for 42.3% [18]. The sediment reduction effect of check dam construction and returning farmland to forests (or grassland) in the Wuding River basin was then analyzed.

Table 4. Contribution rate of climate change and human activities in the Wuding River basin during the study period calculated by the hydrologic method.

Period		Runoff (10^8 m^3)					Sediment Load (10^8 tons)				
		Decreased Value	The Impact of Climate Change		The Impact of Human Activity		Decreased Value	The Impact of Climate Change		The Impact of Human Activity	
			Affected Values	Contribution/%	Affected Values	Contribution/%		Affected Values	Contribution/%	Affected Values	Contribution/%
Study period	1970–2000	4.89	1.11	22.6%	3.78	77.4%	1.256	0.38	30.3%	0.876	69.7%
	2001–2020	7.037	−1.026	−14.6%	8.063	114.6%	1.809	−0.32	−17.7%	2.129	117.7%

4.3.1. Check Dams

A check dam is a soil conservation measure that is built in gullies with the aim of retaining water and trapping sediment. It plays an irreplaceable role in the process of soil erosion control. For example, in the "7.26" torrential rain and flood event in 2017, in the Jiuyuangou watershed, with well-designed check dams, the flood peak and sediment concentration were reduced by 85% and 60%, respectively, compared with a watershed without check dams. Figure 7 shows that the sediment load of the Baijiachuan gauging station decreased with an increase in the control area of main and medium-sized check dams in the Wuding River basin.

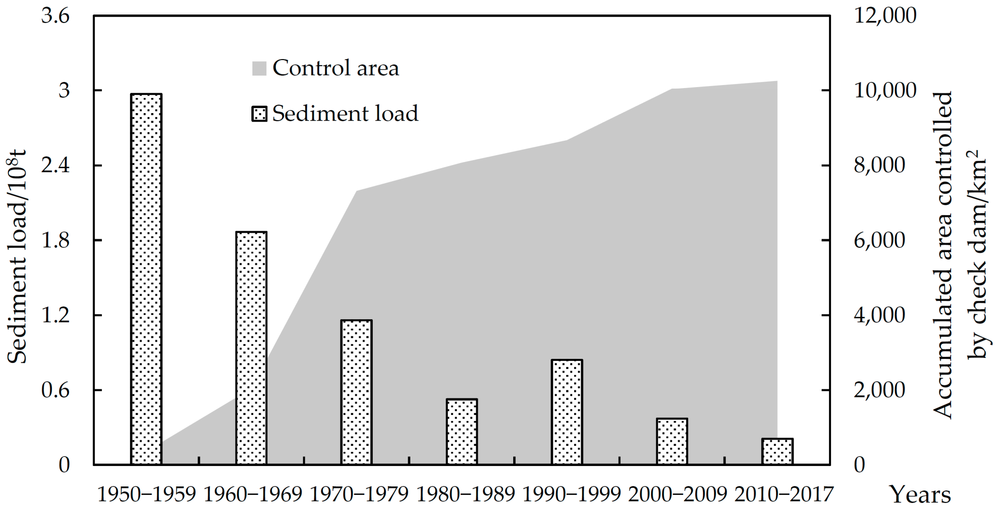

Figure 7. Sediment load at the Baijiachuan gauging station, and the cumulative control area of main and medium-sized check dams in the Wuding River basin.

Check dams in the Wuding River basin can be divided into main, medium-sized, and small-sized check dams. Moreover, a total of 743 main check dams were built during the peak periods of the 1970s and 2000–2009, accounting for 64% of the total number of main check dams. A total of 2859 medium-sized check dams were built during the 1970s and in the period of 2000–2009, accounting for 76% of the total number of medium-sized check dams. By 2017, there were 11,602 check dams, including 1,155 main check dams with a total storage capacity of 1355.0701 million m^3 and a control area of 5424.08 km^2; 3747 medium-sized check dams with a storage capacity of 906,818,900 m^3 and a control area of 4844.77 km^2; 6700 small-sized check dams with a storage capacity of 227.8 million m^3 [19].

Check dams can effectively and efficiently retain water and trap sediment in the early stage of construction. However, the sedimentation in check dams increases with operation time, which leads to the silting-up and failure of a large number of check dams. For example, the storage capacity of check dams in the Wuding River basin increased from 2284 million m^3 in the 1960s to 7806 million m^3 in the 1980s, and decreased to 3160 million m^3 due to sedimentation after the 2000s. Check dam siltation in the Wuding River basin was as follows. (1) The siltation of main check dams was 911,073,000 m^3, accounting for 67.23% of the total reservoir capacity until 2011, and was 21.2174 million t/a from 2011 to 2017. If the sediment unit weight was 1.35 t/m^3, the siltation of main check dams was 1,357,248,900 t until 2017. (2) The siltation of medium-sized check dams was 72,902.84 $\times$ 10^4 m^3, accounting for 80.39% of the total reservoir capacity until 2009, and was 1635.49 $\times$ 10^4 t/a from 2009 to 2017. Therefore, the siltation of medium-sized check dams was 1,357,248,900 t until 2017. (3) Data for small-sized check dams were scarce because of the lack of detailed information on the control area or storage capacity of these check dams. However, the amount of siltation can be estimated according to the total storage capacity and the measurement results of representative small-sized check dams. Field investigation showed that the small-sized check dams in the Wuding River basin were mainly built before 2010, and more than 90% were built before 1990. The function of small-sized check dams in retaining sediment lasts generally only 3–5 years according to the design specifications. Therefore, it can be considered that the siltation of small-sized check dams was approximately 307.53 million t assuming that the storage capacity of 227.8 million m^3 had silted up completely by 2017.

Therefore, the siltation of check dams in the Wuding River basin was approximately 2,747,096,600 t based on the estimated siltation of main, medium-sized, and small-sized check dams, and 50% were main check dams and 40% medium-sized check dams.

4.3.2. Vegetation Measures

Among various water and soil conservation measures, vegetation measures (such as closing hillsides to facilitate afforestation, and returning cultivated land to forests and grassland) have played an important role in the restoration and improvement of the ecological environment. As an important ecological construction project, returning cultivated land to forests has been implemented on a large scale in the Loess Plateau since 1999, and the normalized difference vegetation index (NDVI) of the Wuding River is subsequently increasing (Figure 8). In addition, the change in runoff was inversely proportional to the NDVI before 2006, but subsequently, both increased with increasing rainfall (Figure 8a). Moreover, the variation in sediment load was consistent with that of the NDVI before 2000. However, the sediment load decreased because the vegetation measures played a role in reducing soil erosion after 2000 (Figure 8b).

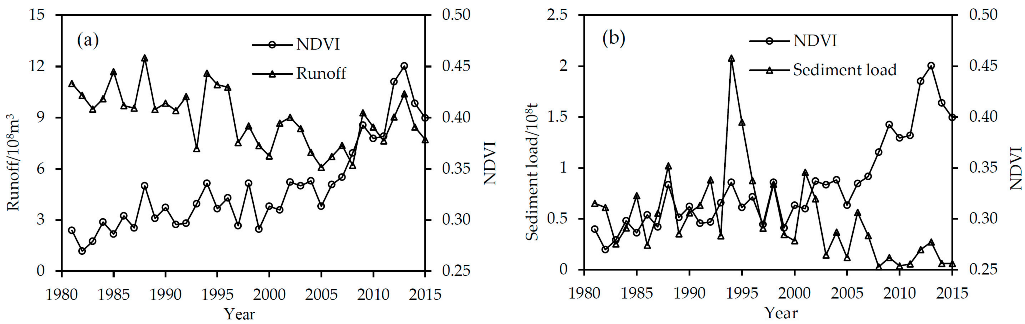

Figure 8. Variation in runoff (or sediment load) and NDVI in the Wuding River basin; (**a**) runoff and NDVI; (**b**) sediment load and NDVI.

Vegetation measures are an important factor affecting the changes in annual runoff and sediment load in the Wuding River basin. Plant roots in the forests and grassland play an important role in improving soil anti-erosion capability and in preventing soil losses. The coverage of existing terraced fields, forest land, grassland, and the closed control area of the Wuding River basin is 1939 km^2, 137,949 km^2, 2815 km^2, and 1997 km^2 respectively, of which the area of forests and grass accounts for 79.4% of the area of soil and water conservation measures. With the implementation and promotion of the project of returning farmland to forests and grassland, the cultivated land in the Wuding River basin decreased, and the forests and grasslands increased significantly (Figure 9). Grassland is the main land use type, accounting for approximately 43% of the total basin area. The reduction in cultivated land area from 1995 to 2013 is a major feature of the project, with a total decrease of 412.32 km^2. The area of forest land has increased with the implementation of the policy of returning cultivated land to forests; it was 1292 km^2, 1747 km^2, and 11,820 km^2 in 1980, 2005, and 2013, respectively.

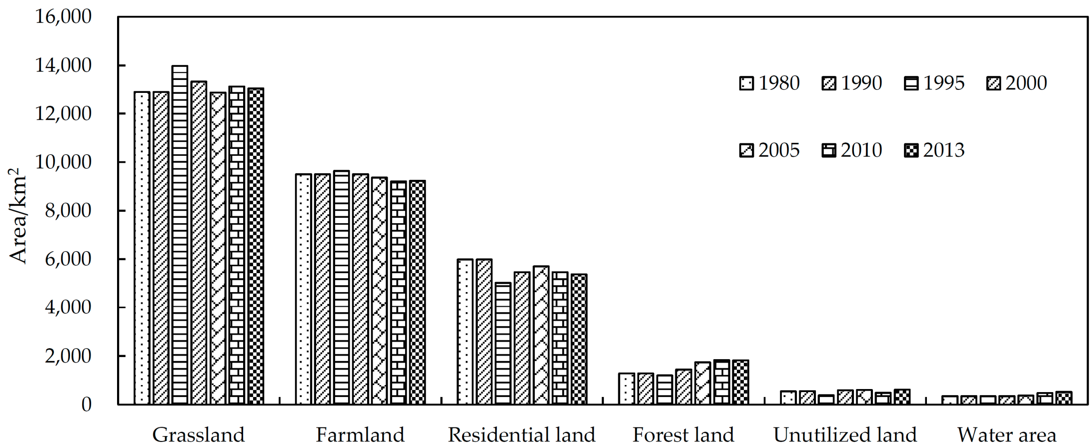

Figure 9. Land use in the Wuding River Basin.

4.4. Sediment Trapping by Reservoirs and Water/Sediment Diversion

For efficient water resource use, a large number of reservoirs and water diversion projects have been built in the Wuding River basin, which has changed the temporal and spatial distribution of runoff and sediment load.

4.4.1. Reservoir Construction

A total of 94 reservoirs had been built in the Wuding River basin by 2011, with a total storage capacity of 1.479 billion m^3. The storage capacity of a large reservoir (Batuwan Reservoir) is 103 million m^3. The total storage capacity of 26 medium-sized reservoirs is 1.221 billion m^3, including eight, twelve, and six reservoirs in the main stream, Luhe River, and Yuxi River, respectively. The total storage capacity of 67 small reservoirs is 155 million m^3, mainly distributed in various tributaries.

Reservoirs have become severely silted-up after years of operation due to soil erosion, which reduces their effective storage capacity. For example, Batuwan reservoir was built in 1972 with a total storage capacity of 103 million m^3. The sedimentation and siltation rate of the reservoir were 52 million m^3 and 50.0%, respectively, by 2011. In addition, 20 out of 138 reservoirs became silted-up based on 1995 data, including Xinqiao, Jiucheng, and Yangfujing reservoirs. The construction and siltation of main reservoirs in the Wuding River basin are shown in Table 5 [20,21]. The average siltation rate of the main reservoirs in the Wuding River basin was approximately 44.3%, which is consistent with previous research results. For example, the average siltation rate of reservoirs was approximately 43.9% based on the statistical analysis of data from 120 reservoirs in northern Shaanxi [22]. Therefore, it can be estimated that reservoir sedimentation was approximately 879 million t until 2011 in the Wuding River, if the reservoir capacity was 1.479 billion m^2, the sedimentation rate was 44.3%, and the unit weight of sediment was 1.35 t/m^3.

4.4.2. Water Diversion Project

Water diversion in the basin has been increasing in recent years with continuous economic development, which is also the reason for the reduction in sediment load. Many water diversion projects have been implemented along the Wuding River since 1949, leading to an increase in the irrigation area. There are 20 diversion canals in the Wuding River basin, including the Dinghui Canal, Luhui Canal, Leihui Canal, Yuxi Canal, Xianghui Canal, and Zhinv Canal. The total irrigation area of the basin was 104.64 kha in 1997, including 37.05 kha for gravity water diversion irrigation, 18.42 kha for pumping irrigation, 40.63 kha for well irrigation, and 8.36 kha for reservoir irrigation. By 2017, around 401 water diversion projects, 1470 pumping stations, and 17,687 mechanical and electrical wells had been built in Yulin City (accounting for 65% of the Wuding River basin area).

Table 5. Construction and siltation of the main reservoirs in the Wuding River basin.

Reservoir	Construction Time	Controlled Area/km^2	Storage Capacity/10^4 m^3	Siltation Rate	Years of Reservoir Operation
Batuwan	1972	3421	10,343	50%	40
Dacha	1985	186	9000	17.2%	14
Jinjisha	1973	205	7544	43.3%	40
Shuilupan	1979	105	6250	59.2%	30
Zhutoushan	1975	216	5440	60%	27
Huiqiao	1972	144	4460	52.1%	30
Shimao	1961	142	2509	32.6%	52
Hekou	1959	1400	2325	20.0%	50
Zhongyingpan	1972	606.7	1900	18%	40
Hongshixia	1958	2060	1900	42.8%	37
Xinqiao	1958	1332	1690	92.3%	17
Average value	/	/	/	44.3%	/

5. Discussion

The comparison method of the slope change rate of accumulation is a basic method to study the impact of climate change and human activities on runoff (or sediment load). In addition, the independent variable of the method is year, and the dependent variables are cumulative runoff and cumulative rainfall. Thus, the use of cumulative variables can eliminate the impact of fluctuations in measured data with the year. The hydrologic method, which has the advantages of simplified models and easy calculation, is an effective method to calculate the contribution rate of runoff and sediment load. The core content is the relationship between rainfall and runoff (or sediment load) in the base period, to ensure the accuracy of simulation.

The average contribution rate calculated by the cumulative curve method and hydrological method was taken as the contribution rate of climate change and human activities to the variation in runoff or sediment load, as shown in Table 6. The impact of human activities on runoff and sediment load changes played a leading role from 1970 to 2020, and the influence is constantly increasing. The contribution rates of human activities to the variation in runoff and sediment load were 69.9% and 75.3%, respectively, from 1970 to 2000, which is consistent with the conclusions that contribution rates were 60–85% and 70–90% of previous research [23–28]. In addition, human activities contributed 118.4% and 114.5% to the reduction in runoff and sediment load, respectively, from 2001 to 2020, which may be related to the implementation of water and soil conservation measures in the Wuding River basin after 2000, such as the policy of returning cultivated land to forests, and check dams [26,27].

Human activities have a greater impact on runoff than sediment load, which is because reservoirs and check dams can intercept sediment, but the flood can flow into rivers through spillways. In addition, in the short term, the check dam is an effective measure to reduce sediment load, but it will lose its effect when the check dam is filled. In the long run, the impact of sustainable ecological construction such as returning farmland to forests and grasslands on runoff and sediment transport will gradually play a leading role [24].

However, the contribution analysis of climate change only considered annual rainfall and ignored evaporation. In addition, when calculating the contribution rate of rainfall to the variation in runoff and sediment load, the annual rainfall was taken as a single variable. The linear regression model of rainfall and runoff (or sediment load) was then used for the attribution analysis. Furthermore, this study did not take into account the impacts of runoff and sediment load by different rainfall intensity, or the hysteresis of water and soil conservation measures, which may cause some deviation. Therefore, to obtain more accurate results of the contribution rate of different factors, further research is required.

Table 6. Causes of runoff and sediment variation in the Wuding River Basin.

Source	Time	Research Method	Influence on Runoff		Influence on Sediment	
			Human Activity	Climatic Change	Human Activity	Climatic Change
Results of this paper	1970–2000 2001–2020	Cumulative curve method	62.3% 122.2%	37.7% −22.2%	80.8% 111.4%	19.2% −11.4%
	1970–2000 2001–2020	Hydrologic method	77.4% 114.6%	22.6% −14.6%	69.7% 117.7%	30.3% −17.7%
	1970–2000 2001–2020	Average	69.9% 118.4%	30.1% −18.4%	75.3% 114.5%	24.7% −14.5%
Mou Xia [23]	1971–2007	Water balance method	63.4%	36.6%	/	/
Jiang kaixin [24]	1972–2010	Cumulative curve method Hydrologic method Elastic coefficient method Water and soil conservation method	81.2% 85.6% 86.8% 48.4%	18.8% 14.4% 13.2% 51.6%	88.7% 73.5% 92.1% 71.1%	11.3% 26.5% 7.9% 28.9%
Sunqian [25]	1971–2010	Method of slope change rate of cumulant Elastic coefficient method	65.8% 63.7%	34.2% 36.3%	90.3% 89.2%	9.7% 10.8%
Jinzhao [26]	1961–2012	Elastic coefficient method Sensitivity analysis method Method of slope change rate of cumulant	78.7% 79.0% /	21.3% 21.0% /	/ / 87.8%	/ / 12.2%
Gaopeng [27]	1980–1989 1990–1999 2000–2006	Cumulative curve method	73.5% 69.4% 98.9%	26.5% 30.6% 1.1%	80.4% 71.8% 88.9%	19.6% 28.2% 11.1%
Ren Zongping [28]	1980–1996 1997–2012	Elastic coefficient method	66.8% 98.2%	33.2% 1.8%	/ /	/ /

6. Conclusions

The contribution rate of climate change and human activities calculated by different methods to runoff and sediment load is given in this study, and the sediment retention of the check dams and the reservoirs are given quantitatively, which is of great significance to the water resources utilization and the construction of ecological civilization in the Wuding river basin.

The runoff and sediment load at the eight gauging stations in the Wuding River basin decreased obviously from 1960 to 2020, with the M–K test values varying from −7.42 to −3.88, and from −9.28 to −3.34, respectively. In particular, runoff decreased continuously before 2010 and then increased slightly, while sediment load decreased continuously from 1960 to 2020. Compared with the 1960s, sediment load at the eight gauging stations decreased by more than 85% from 2010 to 2020.

The impact of human activities on runoff and sediment load changes plays a leading role from 1970 to 2020, and the influence is constantly increasing. The contribution rate of climate change to the decrease in runoff and sediment load in the Wuding River basin was 30.1% and 24.7%, respectively, from 1970 to 2000, and the contribution rate of human activities was 69.9% and 75.3%, respectively. Since 2001, the impact of human activities on the underlying surface has intensified under the policy of reverting farmland to forests. Furthermore, runoff and sediment load continued to show a decreasing trend, despite an increase in rainfall. Therefore, the contribution rate of human activities to the reduction in runoff and sediment load reached 118.4% and 114.5%, respectively, from 2001 to 2020.

Check dams, reservoir construction, reforestation, water diversion, and other human activities are all significant factors in the reduction in runoff and sediment load. Particularly, the cumulative sediment retention of the reservoirs was approximately 879 million tons in

2010, and the cumulative sediment retention of the check dams was approximately 2747 million tons in 2017.

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