sustainability

MDPI

Article

Quantitative Contributions of Climate and Human Activities to Streamflow and Sediment Load in the Xiliugou Basin of China

Wenjun Wang [1,2], Zezhong Zhang [3], Zipeng Wang [3], Hexin Lai [3], Kai Feng [3], Jihong Qu [3], Rong Hao [4], Yong Liu [4], Dequan Zhang [4] and Fei Wang [3,*]

[1] Yinshanbeilu Grassland Eco-Hydrology National Observation and Research Station, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; wangwj@iwhr.com
[2] Institute of Water Resources of Pastoral Area Ministry of Water Resources, Hohhot 010020, China
[3] School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; zhangzezhong@ncwu.edu.cn (Z.Z.); wangzp0330@163.com (Z.W.); x201910102868@stu.ncwu.edu.cn (H.L.); fengkai@ncwu.edu.cn (K.F.); qujihong@ncwu.edu.cn (J.Q.)
[4] Ordos Development Center of Water Conservancy, Ordos 017001, China; haorong@163.com (R.H.); liuyong@163.com (Y.L.); zhangdequan@163.com (D.Z.)
* Correspondence: wangfei@ncwu.edu.cn; Tel.: +86-1-823-692-7593

Abstract: Investigating the influence of human activities and climate change on streamflow and sediment load is of great significance for understanding the hydrological cycle, addressing climate change, and ensuring sustainable water resource management. Based on observed data of precipitation, streamflow, and sediment load from 1990 to 2021 in the Xiliugou Basin, trend and abrupt change analyses of streamflow and sediment load were conducted using the coefficient of variation and Bayesian change point detection method. The effects of climate change and human activities on streamflow and sediment load were further examined through the double mass curve method, with a focus on the impact of land use changes on streamflow and sediment load dynamics. The results indicated that: (1) During the study period, there was a consistent decreasing trend in streamflow, sediment load, and precipitation, with respective rates of -77.76×10^4 m^3/year, -55.97×10^4 Mt/year, and -0.84 mm/year. The distribution of annual streamflow and sediment load in the basin was uneven, with 61.05% of precipitation occurring during the wet season and the peak sediment discharge month being July, accounting for 58.90% of the total annual sediment load. (2) The variations in streamflow and sediment load in the Xiliugou Basin exhibited distinct stage characteristics, with abrupt changes occurring around 1997. Both streamflow and sediment load showed significant fluctuations from the reference period to the changing period, decreasing by 45.54% and 82.85%, respectively. (3) A positive correlation between precipitation and streamflow was observed in the Xiliugou Basin, with correlation coefficients (R) of 0.62 and 0.49, indicating a stimulating effect of precipitation on streamflow and sediment load. Human activities significantly reduced sediment load in the Xiliugou Basin from 1998 to 2021, contributing to a reduction of 115.08%. (4) An increase in cropland, water, and barren areas would lead to higher streamflow and sediment load, while an increase in grassland, forest, and impervious areas would decrease both streamflow and sediment load.

Keywords: streamflow and sediment load; climate change; human activities; land use

check for updates

Citation: Wang, W.; Zhang, Z.; Wang, Z.; Lai, H.; Feng, K.; Qu, J.; Hao, R.; Liu, Y.; Zhang, D.; Wang, F. Quantitative Contributions of Climate and Human Activities to Streamflow and Sediment Load in the Xiliugou Basin of China. *Sustainability* **2024**, *16*, 4645. https://doi.org/10.3390/su16114645

Academic Editor: Hariklia D. Skilodimou

Received: 6 April 2024
Revised: 20 May 2024
Accepted: 28 May 2024
Published: 30 May 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

River water resources are the basis for human production and life as well as the maintenance of ecological balance [1,2]. River streamflow and sediment load are important parts of the global biogeochemical cycle [3–5]. Over the last hundred years, the global climate has changed profoundly, with increased temperatures and increased precipitation frequency greatly affecting hydrological processes [6]. For every 2 °C of warming, streamflow and sediment load will increase by 20% and 10%, respectively [7]. In addition, human activities, including water conservancy engineering construction, land development and utilization,

and water resource management, have also had a dramatic influence on streamflow and sediment load, consequently significantly altering the hydrological characteristics of global rivers [5,8]. Therefore, it is crucial to study river streamflow and sediment load change characteristics and driving factors for better responding to global climate change and management of water resources.

River systems are natural systems with external influences and exist in a state of fluctuation [9–11]. Changes in river runoff and sediment load are important expressions of changes in the main driving factors (climatic factors, especially precipitation, and anthropogenic factors), and are one of the hotspots of global change research [12,13]. Accurately and quantitatively distinguishing the influences of human activities and climate change on runoff and sediment load provides important guidance for management departments and is the key to achieving sustainable development goals [14]. To date, studies have been carried out in different regions on the impacts of climate change and human activities on river streamflow and sediment load. For example, Zhang et al. showed that human activities, especially the construction of hydraulic structures, can have a significant impact on sediment load changes in the downstream Yangtze River [15]. Eccles et al. found that a warming climate may lead to decreased flow in subtropical rivers [16]. Different scholars have adopted different methods to evolute the influences of climate change and human activities, mainly including statistical analysis [17–19], the Budyko hypothesis [20,21], hydrological models [22,23], and so on. Among these, the Double Mass Curve (DMC) of statistical analysis is simple to compute and allows assessment with fewer inputs [14,24]. DMC has been widely used in the attribution analysis of streamflow and sediment load change and has shown great applicability. For mutation point detection, the Bayesian change point detection method can detect the nonlinear and nonstationary characteristics of time series and has the advantage of considering the uncertainty and error range of mutation points [25].

At the same time, there is still a strong relationship between land use and sediment load, and correlations need to be established to fully understand their correlation. Several studies have shown that land use change and climate diversity are also important causes of hydrological change [18]. A reduction in impervious areas may lead to increased streamflow and consequent flooding [26]. The process of river sediment transport is sensitive to many factors, one of which is land use change [27,28]. In Malaysia, a decrease in forest area has led to an increase in sediment load [29]. To summarize, land use is also a key factor influencing streamflow and sediment load. Given this, it is necessary to investigate the impact of land use changes on runoff and sediment load in the Xiliugou Basin, which helps to accurately evaluate the influencing factors of water and sediment relationships.

The Ten Kongduis subregion of Inner Mongolia, located in the north of the Ordos City region, is a sandy and coarse sand area with complex geological conditions, little and concentrated precipitation, sparse vegetation, and poor erosion-resistant soils [30]. Therefore, it is a typical vulnerable ecological area in the midstream and upstream of the Yellow River. Xiliugou Basin is the 4th Kongdui in the Ten Kongduis in the order from west to east. The Xiliugou Basin is dry and sandy, with concentrated and often short-duration, high-intensity precipitation [31]. There is still a lack of systematic research on streamflow and sediment load change and attribution analysis in the Xiliugou Basin. Therefore, we conducted a study on the dynamics and drivers of streamflow and sediment load changes in Xiliugou. The main studies include (1) the dynamic change of streamflow and sediment load; (2) the driving effect of climate change and human activities; and (3) the influences of land use on streamflow and sediment load. The results can provide theoretical support for the improvement of climate change response capacity and ecological environmental protection.

2. Methodology

2.1. Study Region

The Xiliugou Basin (109°23′–109°51′ E, 39°46′–40°19′ N) is one of the Ten Kongduis [32]. With a total area of approximately 1214 km^2, the basin is predominantly located within the Dongsheng District of the Ordos City and Dalad Banner (region). The main stream has a length of about 106.5 km, with an average channel gradient of 3.58%. The terrain slopes from south to north, with elevations ranging between 1000 and 1500 m, resulting in a vertical elevation difference of about 500 m. The basin experiences a typical arid continental monsoon climate characterized by dryness, strong winds, and abundant sand. The average annual precipitation is 305.9 mm, with 76% of the rainfall occurring from June to September. The annual evaporation ranges from 2149.2 to 2234.2 mm, which is more than seven times the precipitation amount. The maximum flood peak in the Xiliugou Basin reaches 6940 m^3/s, while the maximum sediment concentration is 1550 kg/m^3, and the maximum sediment load is 4.75 × 10^7 t/year. The topography within the basin consists mainly of hilly areas, the windy and sandy region of the Kubuqi Desert, and the river plain area. The hilly ravine area in the upstream section of the Xiliugou Basin accounts for about 65% of the total basin area, characterized by dense dendritic water systems, intense incision, well-developed valley landforms, severe soil erosion, and extensive occurrences of loess, leading to the formation of high-sediment-yielding water flow, making it the main sediment production area in the basin [30,31]. The geographical location of the Xiliugou Basin and the distribution of hydrological stations are shown in Figure 1.

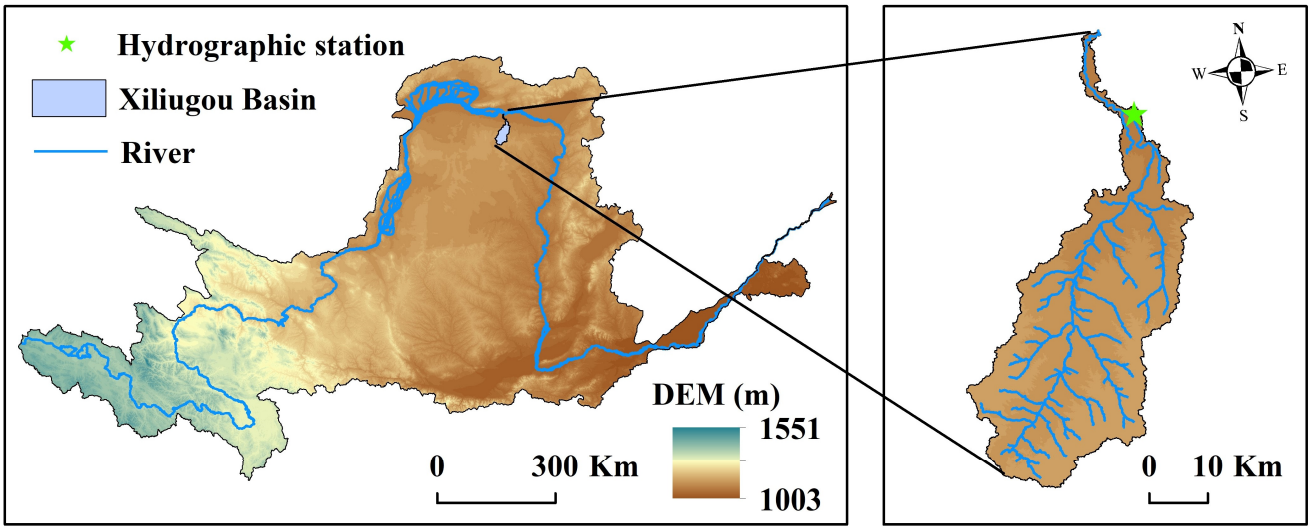


Figure 1. Locations and hydrographic stations of the study area.

2.2. Dataset

The study utilized monthly precipitation, streamflow, and sediment load data from the Longtouguai Hydrological Observation Station in the Xiliugou Basin from 1990 to 2021, analyzed at different time scales. The Longtouguai Hydrological Station is located at the exit section of the Xiliugou Basin, which can better represent the hydrological information in this basin. The linear interpolation method was used to supplement missing data. Meanwhile, the minimum–maximum normalization method was used to preprocess data. To avoid errors caused by manual measurement, we checked the data that exceeded the upper and lower quartiles to ensure the accuracy of the data. After data preprocessing, we have synthesized seasonal and annual precipitation, streamflow, and sediment load. In this study, spring is defined as March to May, summer as June to August, autumn as September to November, and winter as December to February of the following year. Considering the local conditions, the wet season was designated from May to September, while the dry season was set from December to February of the following year [33]. The DEM data

were sourced from the SRTM DEM dataset with a spatial resolution of 90 m [34]. Land use data were obtained from the China Soil Cover Dataset (CLCD) with a spatial resolution of 30 m [35]. Compared to other datasets, this dataset provides higher temporal and spatial resolutions while ensuring the necessary time span for the study, meeting the research requirements effectively.

2.3. Methods

2.3.1. Coefficient of Variation (CV)

CV is a statistical method used to assess the degree of dispersion in long-term sample data, reflecting the distribution of the sample data [20,36]. It serves as a standard for judgment: if the CV is less than or equal to 0.2, this indicates a relatively uniform distribution of sample data with low fluctuations; if the CV is greater than 0.2, this suggests an uneven distribution of the sample data. Furthermore, the coefficient of variation can also indicate the degree of variation in sample data, where a larger CV signifies greater variability in the sample data. For detailed calculation procedures, please refer to [36].

2.3.2. Bayesian Change Point Detection

Bayesian Change Point Detection is a method for detecting abrupt changes or structural variations in time series data [37]. It is based on Bayesian statistical methods, determining the position and number of change points by considering the prior and posterior distributions of the data. This method can be applied to various types of time series. Through this approach, time series can be decomposed into different components, namely, trend, seasonality, and residual [38,39]. The trend represents the long-term trend changes in the time series, seasonality denotes the repetitive patterns within fixed periods, and the residual signifies random fluctuations that cannot be explained by the trend and seasonality. Time-series decomposition can help us better understand the structure and characteristics of time series, as well as facilitate prediction and analysis of the sequences. For detailed calculation procedures, please refer to [39]. Furthermore, the formula for the Bayesian method is as follows:

$$Y_\tau = T_\tau + S_\tau + \varepsilon \tag{1}$$

where Y_τ is the original signal, and T_τ, S_τ, and ε are the trend signal, seasonal signal, and residual signal, respectively. The linear expression for the trend component T_τ is as follows:

$$T_\tau = \alpha_i + \beta_i t \ (\tau_{i-1} < t < \tau_i, \ I = 1, \ldots, m) \tag{2}$$

where α_i and β_i are the intercept and slope on both sides of a mutation point, respectively, and i is the location of a mutation point.

The seasonal component S_τ is as follows:

$$S_\tau = \sum_{k=1}^{K} \gamma_k \sin\left(\frac{2\pi k\tau}{f} + \delta_k\right) \tag{3}$$

where γ_k, f, and δ_k are the amplitude, frequency, and phase, respectively.

2.3.3. Correlation Analysis

The calculation of correlation coefficients most commonly employs the method of moments introduced by the British statistician Karl Pearson. When the correlation coefficient R is less than 0, it indicates a negative correlation between the two variables; when R is larger than 0, it indicates a positive correlation between the variables. Additionally, the larger $|R|$, the stronger the correlation between the two variables. When $|R|$ falls between 0 and 0.3, the variables are weakly correlated; when $|R|$ ranges from 0.3 to 0.5, the variables are moderately correlated; when $|R|$ falls between 0.5 and 0.8, the variables are strongly correlated; and when $|R|$ is between 0.8 and 1, the variables are highly correlated. In this study, correlation coefficients were used to assess the relationships between precipitation and streamflow

and precipitation and sediment load. The method was also employed to calculate the R between land use and precipitation, streamflow, and sediment load. The detailed calculation procedures for this method can be found in [40].

2.3.4. Double Mass Curve (DMC)

The DMC method is one of the simplest, most effective, and most used approaches for analyzing continuous or long-term trends in hydrometeorological factors [18,24]. DMC is a relationship line in Cartesian coordinates that provides the continuous cumulative values of one variable and the continuous cumulative values of another variable during the same period. Constructing the DMC aims to eliminate the impact of the reference variable to determine whether other factors are causing significant changes in the trend of the measured variable.

By utilizing Bayesian change point detection to identify the years of abrupt changes, streamflow and sediment load sequences are divided into two phases, with the period before the abrupt change being referred to as the baseline period, while the period after the abrupt change is termed the changing period.

A linear regression analysis is conducted on the cumulative sediment load ΣS and cumulative precipitation ΣP of the baseline period to obtain their relationship:

$$\Sigma P = k\Sigma S + b \tag{4}$$

Applying Equation (4) to the changing period, the cumulative sediment load is calculated based on the cumulative precipitation after the change year, assuming the sediment load remains the same as before the change without any anthropogenic interference.

The annual sediment load can be back-calculated from the calculated cumulative sediment load and the difference between the observed and theoretical values of average annual sediment load (S) after the change year is determined. As Equation (4), the calculation of annual sediment load, only considers precipitation, the difference between the observed sediment load before and after the change year reveals the sediment load contributions from precipitation and human activities:

$$\Delta H = S_2M - S_2T \tag{5}$$

$$\Delta W = S_2T - S_1M \tag{6}$$

where ΔH and ΔW are the human and natural factors that cause changes in sediment load, respectively; and S_1M, S_2M, and S_2T are the average measured sediment load values during the reference period, the average measured sediment load values during the change period, and the theoretical values, respectively.

To quantitatively analyze the driving factors behind sediment load changes, the impacts of precipitation and human activities on sediment load are compared with the differences in observed sediment load values, using percentages to indicate the contributions of precipitation and human activities to sediment load during specific time periods:

$$R_H = \frac{\Delta H}{SD} \times 100\% \tag{7}$$

$$R_W = \frac{\Delta W}{SD} \times 100\% \tag{8}$$

where R_H is the contribution of human activities to sediment load; R_W is the contribution of climate change to sediment load; and SD is the difference between the measured values of sediment load before and after a sudden change year.

3. Results

3.1. Dynamic Variation Characteristics of Hydrological and Meteorological Variables

3.1.1. Variation Trends of Streamflow and Sediment Load

The streamflow, sediment load, and precipitation in the Xiliugou watershed showed decreasing trends from 1990 to 2021, with change rates of -77.76×10^4 m^3/year, -55.97×10^4 Mt/year, and -0.84 mm/year, respectively. The overall trends were consistent, with precipitation exhibiting non-significant changes ($p > 0.05$), while streamflow and sediment load showed significant changes ($p < 0.05$) (Figure 2). The multi-year average streamflow and sediment load in the basin were 2189.07×10^4 m^3 and 541.86×10^4 Mt, respectively. The interannual variations in streamflow and sediment load were substantial, with the annual streamflow ranging from 536.18×10^4 m^3 to 7187.10×10^4 m^3, with the maximum value in 2016 being approximately 13 times the minimum value in 2021. The annual sediment load varied between 0.01×10^4 Mt and 6184.86×10^4 Mt, with the maximum value in 1994 being approximately 481,075 times the minimum value in 2011. Furthermore, the CV revealed greater fluctuations in sediment load (mean CV of 2.36) compared to streamflow (mean CV of 0.83) (Table 1).

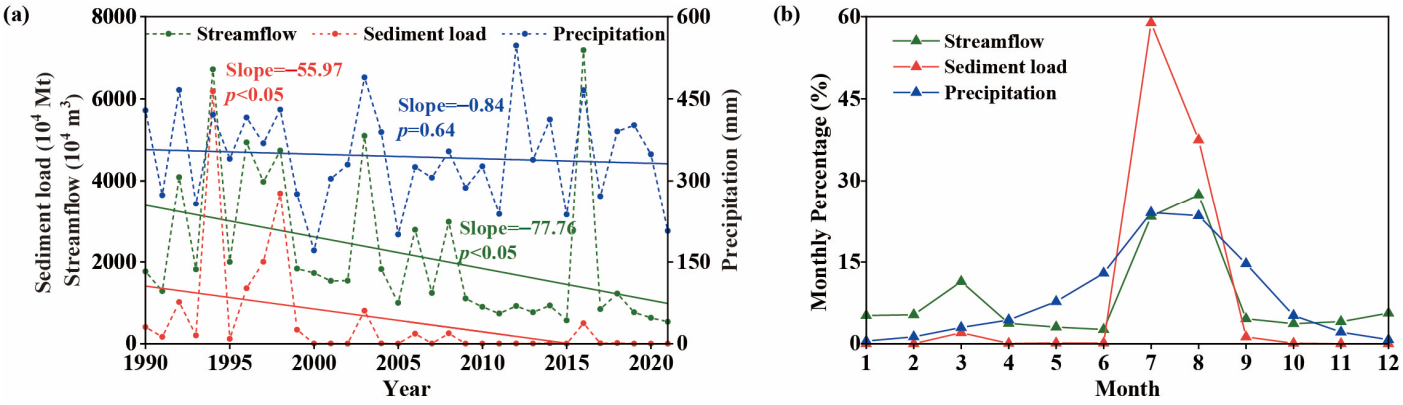


Figure 2. Changing trends of sediment load, streamflow, and precipitation (**a**) interannual variation and (**b**) monthly distribution in the Xiliugou Basin.

Table 1. Characteristics of streamflow, sediment load, and precipitation in the Xiliugou Basin.

	Streamflow		Sediment Load		Precipitation	
	Mean (10^4 m^3)	CV	Mean (10^4 Mt)	CV	Mean (mm)	CV
Year	2189.07	0.83	541.86	2.36	344.48	0.26
Wet season	1336.37	1.24	530.41	2.40	285.70	0.32
Dry season	351.95	0.53	0	3.44	8.47	0.64
Spring	398.10	0.45	11.66	1.78	51.83	0.59
Summer	1170.06	1.40	523.03	2.44	208.54	0.41
Autumn	268.96	0.48	7.16	2.98	75.64	0.39
Winter	351.95	0.53	0	3.44	8.47	0.64

A total of 61.05% of the annual streamflow in the Xiliugou Basin occurs during the wet season, which is more than three times higher than that of the dry season (Table 1 and Figure 2). Spring streamflow contributes the most within a year, accounting for 53.45% of the annual streamflow. In terms of monthly streamflow, August exhibits the highest flow, followed by July, representing 27.45% and 23.40% of the annual streamflow, respectively. Furthermore, 97.89% of the annual sediment load is concentrated in the wet season. Almost all sediment load occurs during the summer, with summer sediment load constituting 96.53% of the annual total. Winter sediment load is nearly negligible, with extreme interannual variations (extreme value ratio of 3.44), indicating both low winter sediment load and substantial interannual variability. Moreover, the sediment load

within the year is highly uneven, with the maximum monthly sediment load occurring in July, representing 58.90% of the annual total. August follows, accounting for 37.51% of the annual sediment load. The trends in precipitation align closely with those of streamflow and sediment load. Summer precipitation dominates, encompassing 60.54% of the total annual precipitation. In terms of monthly precipitation, July experiences the highest volume, contributing 24.10% of the total annual precipitation, followed by August at 23.50%.

3.1.2. Mutation Characteristics of Streamflow and Sediment Load

Bayesian Change Point Detection was conducted on the streamflow and sediment load data in the Xiliugou watershed from 1990 to 2021 (Figure 3). The results indicate a 71.4% probability of one change point in the seasonal component of annual streamflow, occurring in 1994. For the trend component of annual streamflow, there is a 45.9% probability of one change point, which took place in 1996. As this probability is below 50%, the change point is not displayed in Figure 3a. Regarding annual sediment load, the probabilities of one change point in the seasonal and trend components are 72.4% and 51.1% respectively, with events occurring in 1997 and 1999. It is observed that the years of abrupt changes in annual streamflow and sediment load are quite consistent, both around 1997. Therefore, the period from 1990 to 1997 is selected as the reference period, while the period from 1998 to 2021 is chosen as the changing period.

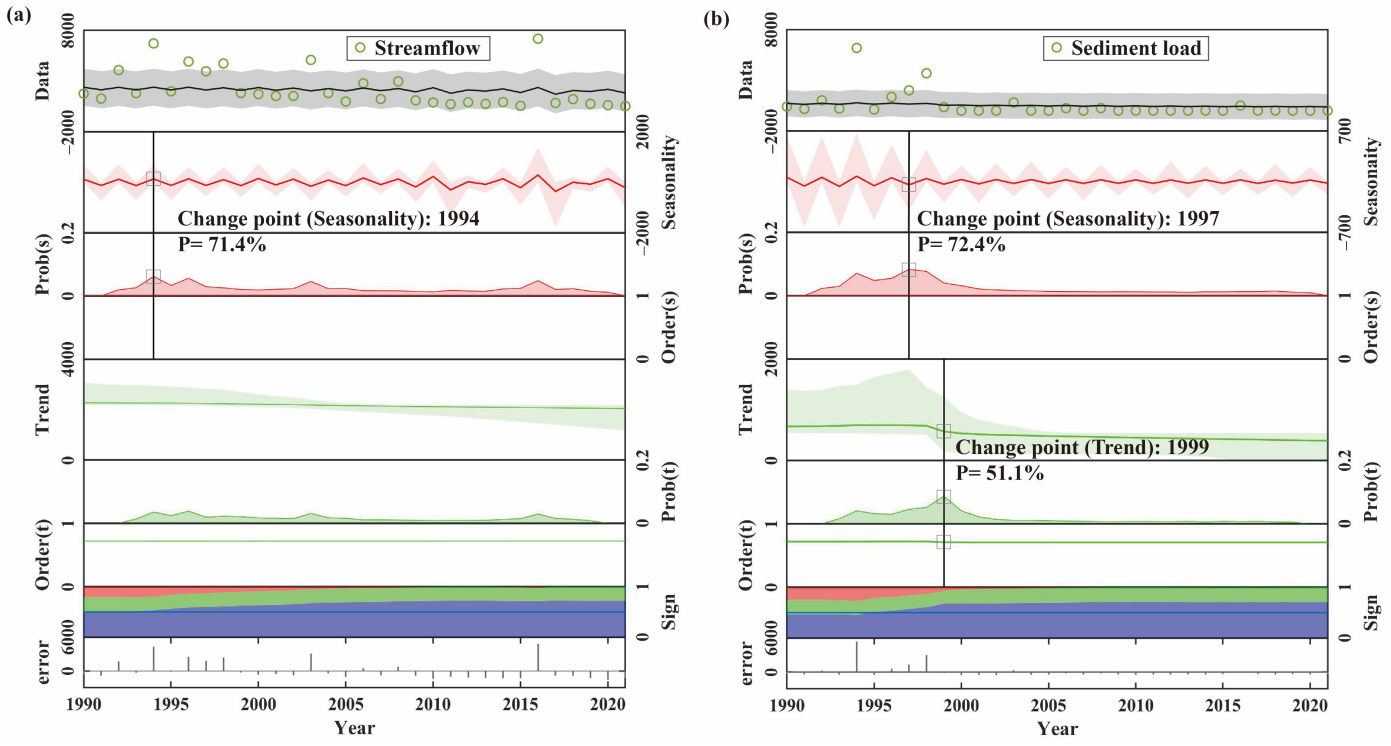


Figure 3. Bayesian Change Point Detection test analysis for (**a**) streamflow and (**b**) sediment load in the Xiliugou Basin. The light-colored area in the figure indicates a 95% confidence interval.

During the study period, both streamflow and sediment load in the Xiliugou Basin exhibited distinct phased characteristics (Figure 4). While showing a certain declining trend throughout the research period (Figure 2), both streamflow and sediment load displayed non-significant increasing trends during the reference period ($p > 0.05$), with change rates of 385.53 $\times$ 10^4 m^3/year and 242.86 $\times$ 10^4 Mt/year, respectively. In the changing period, streamflow exhibited a significant decreasing trend ($p < 0.05$) with a change rate of -77.76×10^4 m^3/year, while sediment load showed a non-significant decreasing trend ($p > 0.05$) with a change rate of -42.64×10^4 Mt/year. Notably, both streamflow and

sediment load demonstrated strong fluctuations from the reference period to the changing period, decreasing by 45.54% and 82.85% respectively.

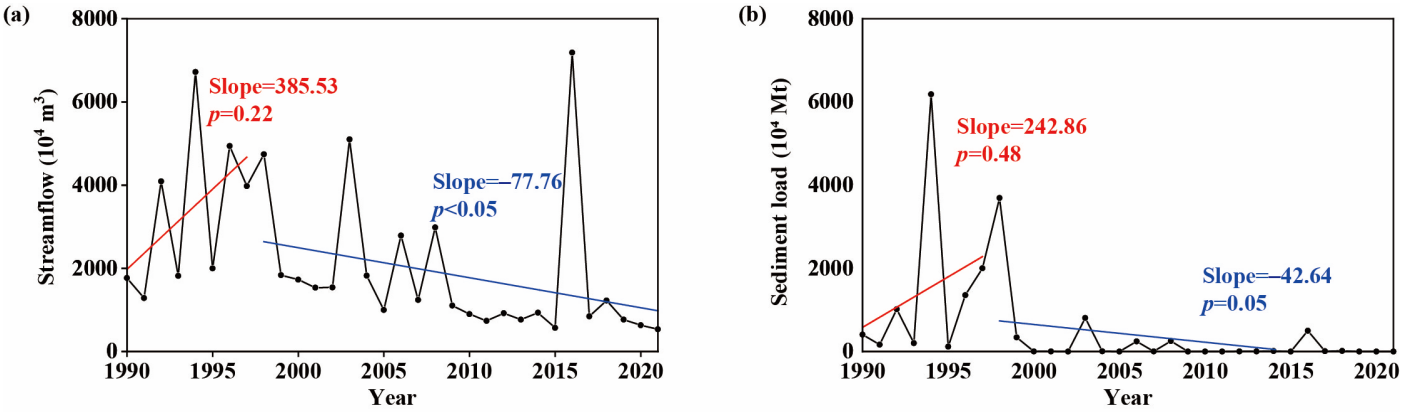


Figure 4. Segmented trend in (**a**) streamflow and (**b**) sediment load in the Xiliugou Basin. The red and blue lines represent changes in the baseline (1990–1997) and change (1998–2021) periods, respectively.

3.2. Contribution of Factors to Streamflow and Sediment Load

Throughout the reference period, changing period, and the entire study duration, a positive correlation was observed between precipitation and streamflow in the Xiliugou watershed (Figure 5a), with respective R values of 0.62, 0.49, and 0.34. Furthermore, the correlation between precipitation and streamflow volume was significant throughout the entire study phase ($p < 0.01$). Similarly, a positive correlation was found between precipitation and sediment load in the Xiliugou watershed, albeit with a lower correlation value compared to precipitation and streamflow, with R values of 0.46, 0.32, and 0.34, respectively (Figure 5b). Again, the correlation between precipitation and sediment load was significant over the entire study phase ($p < 0.1$). Overall, precipitation was found to have a promoting effect on both streamflow and sediment load. Additionally, it was observed that the correlations, whether between precipitation and streamflow or between precipitation and sediment load, were lower in the changing period than in the reference period. This suggests that the impact of climate change on streamflow and sediment load during the reference period may be higher than that during the changing period.

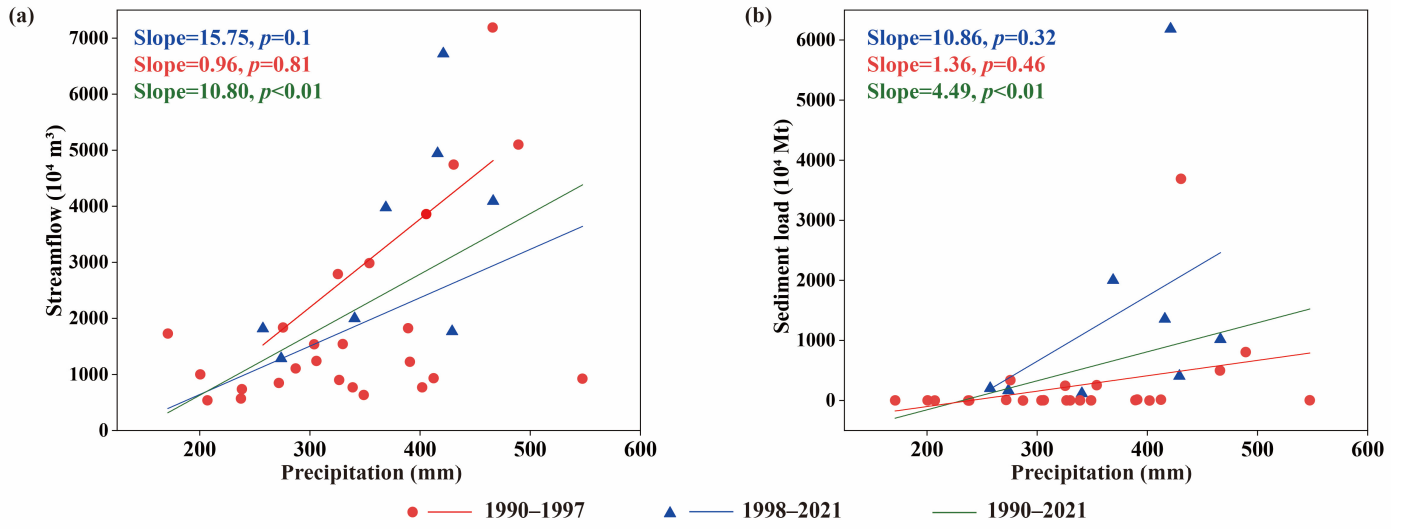


Figure 5. Relationship between (**a**) precipitation and streamflow, and (**b**) precipitation and sediment load.

In both the reference and changing periods, the DMC for precipitation and streamflow in the Xiliugou watershed exhibited a linear relationship, with slopes of 10.09 and

5.02 during the reference and changing periods, respectively (Figure 6). Following the inflection point, there was a decrease in slope by 5.07. Similarly, the cumulative curves for precipitation and sediment load also showed a linear relationship in both the reference and changing periods, with slopes of 4.48 and 0.27 during the reference and changing periods, respectively. Again, a decreasing trend in slope was observed post the inflection point, with a decrease of 4.2.

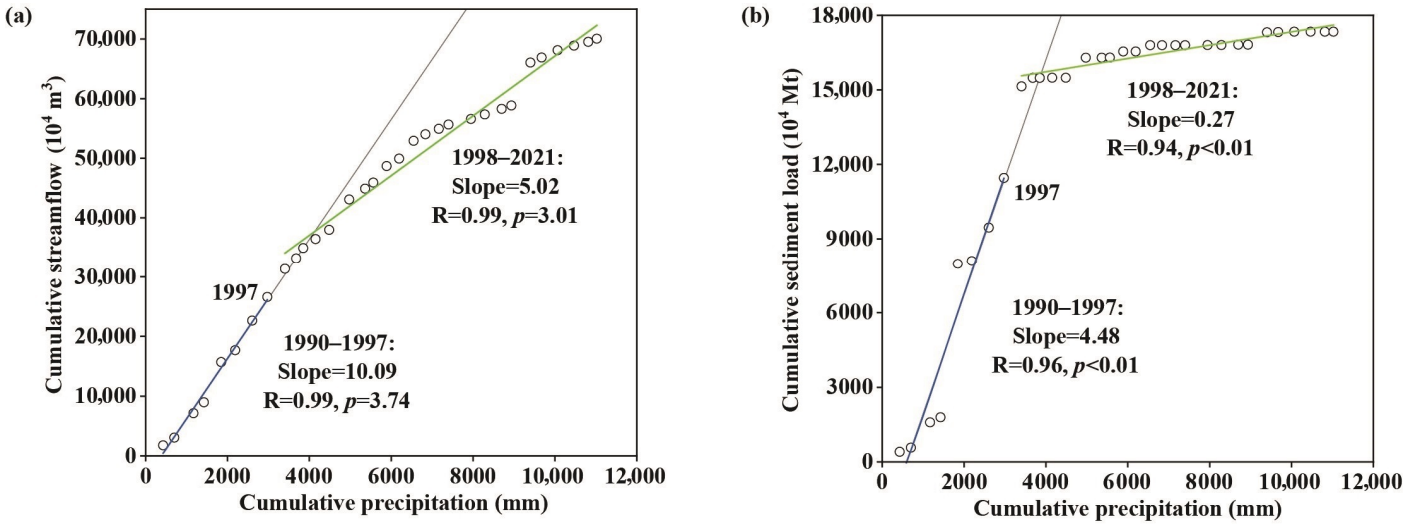


Figure 6. Cumulative annual precipitation and streamflow (**a**), and sediment load (**b**) in the Xiliugou Basin from 1990 to 2021.

The analysis of the DMC indicates that in the changing period of the Xiliugou Basin, sediment load decreased by 1185.82 × 10^4 Mt/year compared to the reference period (Table 2). In the absence of human activities, the sediment load in the Xiliugou Basin would increase by 178.81 × 10^4 Mt/year from 1998 to 2021, with climate change contributing 15.08% to the sediment load. Human activities have significantly reduced sediment load in the Xiliugou watershed from 1998 to 2021, with human activity accounting for 115.08% of the contribution.

Table 2. Influence of climate change and human activities on sediment load in the Xiliugou Basin.

Period	S_o (10^4 Mt/a)	S_c (10^4 Mt/a)	Human Activities		Climate Change	
			ΔS_h (10^4 Mt/a)	CR_h (%)	ΔS_c (10^4 Mt/a)	CR_c (%)
1990–1997	1431.22					
1998–2021	245.40	1610.03	−1364.63	115.08	178.81	−15.08

3.3. Influence of Land Use on Streamflow and Sediment Load

3.3.1. Land Use Changes

Grassland is the major land use in the Xiliugou Basin, with an average area percentage of 77.28% from 1990 to 2021, accounting for more than half of the regional area (Figure 7). Meanwhile, cropland and barren are also the main land use types in the Xiliugou Basin, with an average area percentage of 12.48% and 9.78% from 1990 to 2021, respectively. During the study period, the grassland, forest, and impervious surface areas in the Xiliugou Basin showed an increasing trend, while the remaining land use types (cropland, water, barren) exhibited a decreasing trend. Specifically, areas of grassland increased by 200.20 km^2, accounting for approximately 12.44% of the study area. As shown in Figure 7, an increase in grassland areas mainly resulted from the conversion of cropland (82.54 km^2) and impervious surfaces (168.10 km^2). It is worth noting that forests first appeared in the Xiliugou Basin in 2013, and by 2021, forest areas had increased to 0.12 km^2. The impervious

surface area in 2021 was 7.51 km^2 more than that in 1990, with these additional impervious areas primarily converted from grassland (3.95 km^2) and barren land (3.24 km^2).

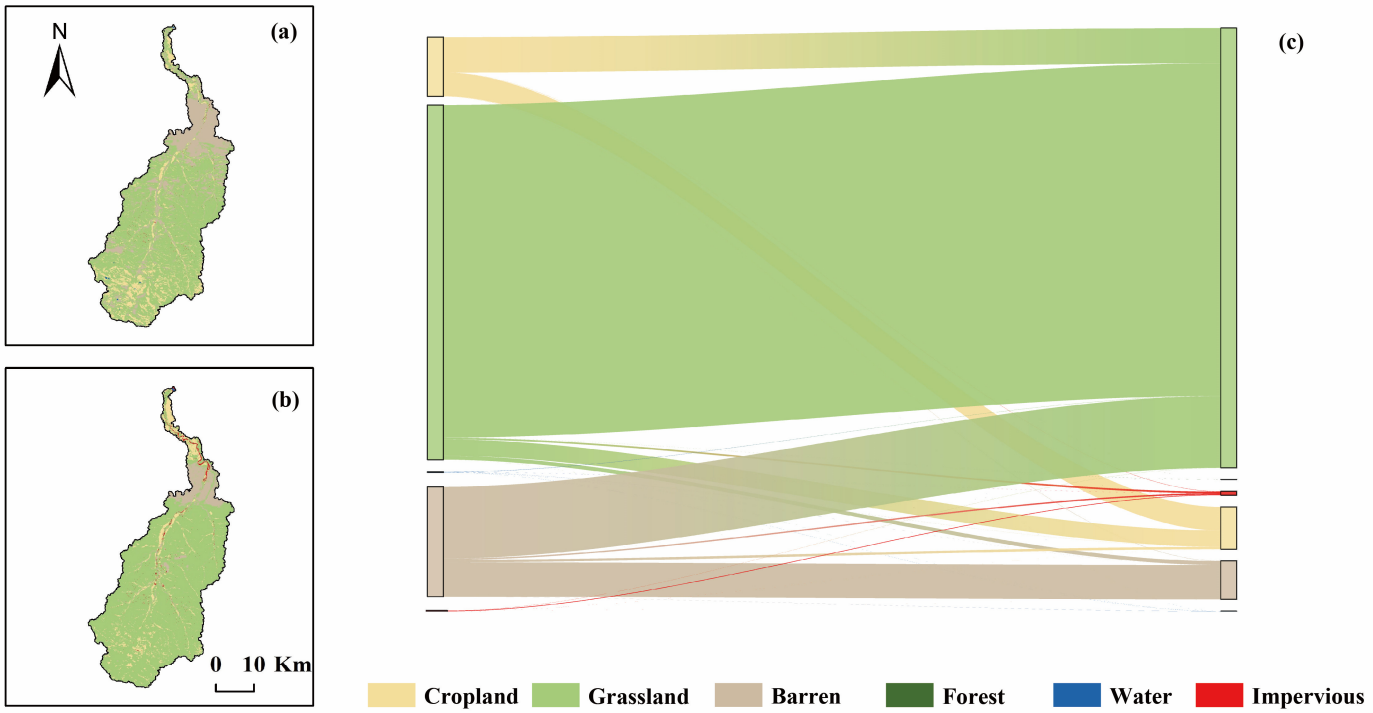


Figure 7. The distribution of land use in the Xiliugou Basin. (**a**,**b**) represent 1990 and 2021, while (**c**) represents the dynamics of land use transfer from 1990 to 2021.

3.3.2. Correlation Analysis

The correlation coefficients between land use area and streamflow, sediment load, and precipitation in the Xiliugou Basin from 1990 to 2021 are shown in Figure 8. The areas of cropland, water, and barren land are positively correlated with streamflow, with water areas exhibiting a moderately positive correlation with streamflow (R = 0.52). Similarly, the areas of these three land use types also show positive correlations with sediment load and precipitation. In particular, water areas and barren land exhibit a moderately positive correlation with sediment load (R = 0.58 and 0.55). In contrast, these land use types show weaker correlations with precipitation, with R values all less than 0.3 (0.11–0.17). Conversely, the areas of forest, grassland, and impervious surfaces are negatively correlated with streamflow. Notably, impervious surface areas demonstrate the strongest negative correlation with streamflow, reaching a weak negative correlation (R = −0.42). These three land use types also exhibit negative correlations with sediment load and precipitation. In terms of negative correlation with sediment load, once again, impervious surface areas show the strongest correlation (R = −0.41). Meanwhile, the correlations between forest, grassland, and impervious surface areas and precipitation are relatively weak, with R values ranging from −0.02 to −0.04. Overall, the correlations between land use and streamflow and sediment load are stronger than those between land use and precipitation. Increases in cropland, water areas, and barren land lead to increased streamflow and sediment load, while increases in forest, grassland, and impervious surface areas result in decreased streamflow and sediment load. This indirectly confirms our previous results, indicating consistent trends among streamflow, sediment load, and precipitation during the study period.

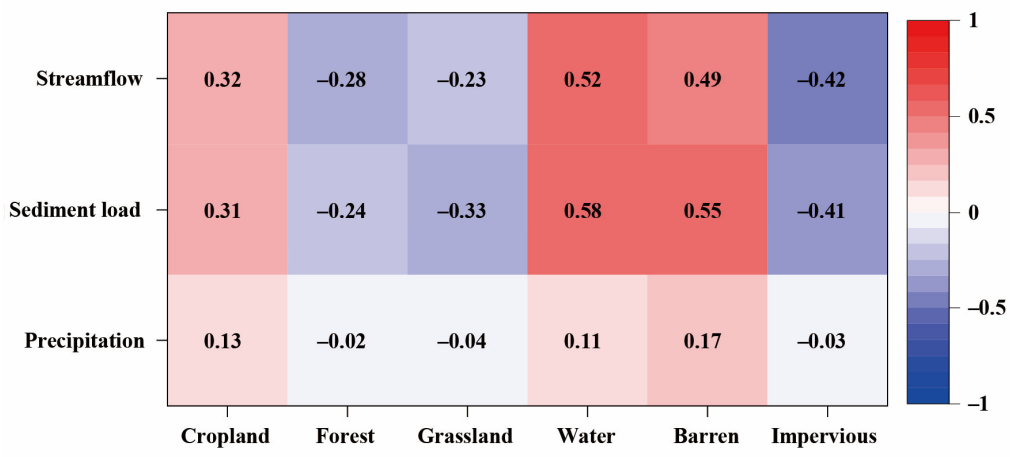


Figure 8. The correlation coefficients in land use with streamflow, sediment load, and precipitation, respectively.

4. Discussion

The variations in river streamflow and sediment load are the combined result of climate change and human activities within a basin. In the context of climate change, the distribution and intensity of precipitation and temperature may change on a global scale [2,3,37]. Therefore, a decrease in precipitation and an increase in temperature will drive streamflows. Meanwhile, as global temperatures continue to rise, glacier melting has become another serious problem [41]. The water released by glacier melting is one of the important sources of streamflows [42]. Our study indicates a decreasing trend in both streamflow and sediment load in the Xiliugou Basin from 1990 to 2021, consistent with the evolution of precipitation patterns. Several findings suggest that the correlation between precipitation and streamflow is stronger than that between streamflow and other meteorological factors (such as temperature or potential evapotranspiration) on both inter-annual and intra-annual scales [43–45]. Therefore, we utilized precipitation as a proxy for climate change to analyze the influence of human activities and climate change on sediment load. By establishing a linear relationship between precipitation and sediment load during the baseline period, the expected natural sediment load during the changing period can be predicted (in Figure 6). The comparison between predicted sediment and actual observed sediment load represents the impact of human activities. The results reveal that human activities significantly reduced the sediment load during the period of change in the Xiliugou Basin. The contribution of human activities exceeds 100%, which is due to the negative contribution of climate change based on the DMC method. In fact, around 1999, comprehensive soil and water conservation measures such as returning farmland to forests, constructing silt dams, and implementing ecological restoration projects were initiated in the basin. Starting from 2000, a large number of silt dams were constructed in the area. In 2008, the concept of "sediment interception and water exchange" was introduced. These measures have visibly improved the soil erosion situation in the Xiliugou Basin, leading to a significant reduction in sediment load. Studies indicate that the "sediment interception and water exchange" project not only intercepted 3.21×10^6 tons of sediment load from the Ten Kongduis but also replaced downstream river sediment load with 2.57×10^7 m^3 of streamflow [30,46]. While these human activities may indirectly influence climate change [47,48], it is undeniable that human activities have played a crucial role in the variation in sediment load in the Xiliugou Basin, aligning with the findings of this study. Currently, human activities have greatly improved the streamflow–sediment load relationship in the Xiliugou Basin, enhancing the quality of the ecological environment.

At the same time, while revealing the impact of climate change and human activities on streamflow and sediment content, it is also necessary to explore a more specific human activity factor that affects streamflow and sediment content [49]. As one of the human activity factors, land use change can lead to changes in hydrological functions within the

watershed. Generally, human activities refer to human interventions in the utilization of the basin, such as changes in land use and the construction of hydraulic engineering projects [5,18]. Previous studies have confirmed the representative role of land use changes in human activities [50–52]. In the Xiliugou Basin, grassland is the primary land use type. During the study period, there was an increasing trend in grassland areas, which to some extent constrained the changes in streamflow and sediment load. It is worth noting that an increase in impermeable areas may also contribute to a reduction in streamflow and sediment load, consistent with previous research findings [26]. In 2013, forests first appeared in the Xiliugou Basin, reflecting the effectiveness of streamflow and sediment management in the area. Additionally, an increase in forests exacerbated the decrease in streamflow and sediment load.

However, relying solely on annual precipitation and land use to represent climate change and human activities has certain limitations [53,54]. In the future, when analyzing streamflow–sediment load relationships and trends in a basin, the complexity of precipitation–streamflow–sediment load processes should be considered. Analysis should focus on the relationship between precipitation during the flood season, maximum daily precipitation, and streamflow and sediment load in order to explore the response mechanisms of streamflow and sediment load to precipitation more comprehensively. By integrating specific human activities and employing indicators related to soil and water conservation measures, afforestation, and ecological restoration, quantitative analyses can be conducted to assess the influencing factors of streamflow–sediment load changes more accurately. This will provide a scientific basis and technical support for streamflow-sediment load management practices.

5. Conclusions

Based on the measured precipitation, streamflow, and sediment load data in the Xiliugou Basin from 1990 to 2021, trend and mutation analyses of streamflow and sediment load were conducted using the CV and Bayesian Change Point Detection methods. The contribution of climate change and human activities to the variations in streamflow and sediment load was assessed based on the DMC method, with an exploration of the impacts of land use changes on streamflow and sediment load dynamics. The conclusions drawn are as follows:

(1) From 1990 to 2021, streamflow, sediment load, and precipitation in the Xiliugou Basin exhibited decreasing trends (with change rates of -77.76×10^4 m^3/year, -55.97×10^4 Mt/year, and -0.84 mm/year, respectively), showing a generally consistent overall trend. Intra-annual distribution of streamflow and sediment load in the basin was uneven, with 61.05% of precipitation occurring during the wet season.

(2) The years of significant change points in annual streamflow and sediment load were consistent, occurring around 1997. Fluctuations were evident in both streamflow and sediment load from the reference period to the change period, with reductions of 45.54% and 82.85%, respectively.

(3) The double cumulative curves revealed that human activities significantly reduced sediment load in the Xiliugou Basin from 1998 to 2021, with human activities contributing 115.08% to this reduction.

(4) The correlation between land use types and streamflow/sediment load was stronger than that with precipitation. Increases in cropland, water area, and barren land led to higher streamflow and sediment load, while expansions in forest, grassland, and impervious areas resulted in decreased streamflow and sediment load.

Author Contributions: Conceptualization, W.W. and F.W.; data interpretation and methodology, H.L. and Z.W.; validation, K.F.; software, J.Q., original draft preparation, W.W. and Z.Z.; funding acquisition, R.H., Y.L. and D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Key Special Project of the "Science and Technology Revitalization of Mongolia" Action (grant number 2022EEDSKJXM004-4), Henan Province Science and Technology Research Projects (grant number 242102321005), and Key Scientific Research Projects in Higher Education Institutions in Henan Province (grant number 24A570005).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We are grateful for the help provided by Ruyi Men in data collection.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. O'Donoghue, C.; Meng, Y.; Ryan, M.; Kilgarriff, P.; Zhang, C.; Bragina, L.; Daly, K. Trends and Influential Factors of High Ecological Status Mobility in Irish Rivers. *Sci. Total Environ.* **2022**, *816*, 151570. [CrossRef] [PubMed]
2. Yin, S.; Gao, G.; Li, Y.; Xu, Y.J.; Turner, R.E.; Ran, L.; Wang, X.; Fu, B. Long-Term Trends of Streamflow, Sediment Load and Nutrient Fluxes from the Mississippi River Basin: Impacts of Climate Change and Human Activities. *J. Hydrol.* **2023**, *616*, 128822. [CrossRef]
3. Milly, P.C.D.; Dunne, K.A.; Vecchia, A.V. Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate. *Nature* **2005**, *438*, 347–350. [CrossRef] [PubMed]
4. Cohen, S.; Kettner, A.J.; Syvitski, J.P.M. Global Suspended Sediment and Water Discharge Dynamics between 1960 and 2010: Continental Trends and Intra-Basin Sensitivity. *Global Planet. Chang.* **2014**, *115*, 44–58. [CrossRef]
5. Yin, S.; Gao, G.; Ran, L.; Li, D.; Lu, X.; Fu, B. Extreme Streamflow and Sediment Load Changes in the Yellow River Basin: Impacts of Climate Change and Human Activities. *J. Hydrol.* **2023**, *619*, 129372. [CrossRef]
6. IPCC. Summary for Policymakers. In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Groups II to the Six Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2022.
7. Syvitski, J.P.M.; Vörösmarty, C.J.; Kettner, A.J.; Green, P. Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean. *Science* **2005**, *308*, 376–380. [CrossRef] [PubMed]
8. Gudmundsson, L.; Boulange, J.; Do, H.X.; Gosling, S.N.; Grillakis, M.G.; Koutroulis, A.G.; Leonard, M.; Liu, J.; Schmid, M.H.; Papadimitriou, L.; et al. Globally Observed Trends in Mean and Extreme River Flow Attributed to Climate Change. *Science* **2021**, *371*, 1159–1162. [CrossRef] [PubMed]
9. Walling, D.E.; Fang, D. Recent Trends in the Suspended Sediment Loads of the World's Rivers. *Global Planet. Chang.* **2003**, *39*, 111–126. [CrossRef]
10. Gao, P.; Zhang, X.; Mu, X.; Wang, F.; Li, R.; Zhang, X. Trend and Change-Point Analyses of Streamflow and Sediment Discharge in the Yellow River during 1950–2005. *Hydrolog. Sci. J.* **2010**, *55*, 275–285. [CrossRef]
11. Xin, Z.B.; Yu, B.F.; Han, Y.G. Spatiotemporal Variations in Annual Sediment Yield from the Middle Yellow River, China, 1950–2010. *J. Hydrol. Eng.* **2024**, *20*, 04014090.
12. Chalov, S.; Prokopeva, K.; Magritsky, D.; Grigoriev, V.; Fingert, E.; Habel, M.; Juhls, B.; Morgenstern, A.; Overduin, P.P.; Kasimov, N. Climate Change Impacts on Streamflow, Sediment Load and Carbon Fluxes in the Lena River Delta. *Ecol. Indic.* **2023**, *157*, 111252. [CrossRef]
13. Feng, Z.; Liu, S.; Guo, Y.; Liu, X. Runoff Responses of Various Driving Factors in a Typical Basin in Beijing-Tianjin-Hebei Area. *Remote Sens.* **2023**, *15*, 1027. [CrossRef]
14. Luan, J.; Zhang, Y.; Ma, N.; Tian, J.; Li, X.; Liu, D. Evaluating the Uncertainty of Eight Approaches for Separating the Impacts of Climate Change and Human Activities on Streamflow. *J. Hydrol.* **2021**, *601*, 126605. [CrossRef]
15. Zhang, Q.; Xu, C.Y.; Singh, V.P.; Yang, T. Multiscale Variability of Sediment Load and Streamflow of the Lower Yangtze River Basin: Possible Causes and Implications. *J. Hydrol.* **2009**, *368*, 96–104. [CrossRef]
16. Eccles, R.; Zhang, H.; Hamilton, D.; Trancoso, R.; Syktus, J. Impacts of Climate Change on Nutrient and Sediment Loads from a Subtropical Catchment. *J. Environ. Manag.* **2023**, *345*, 118738. [CrossRef] [PubMed]
17. Du, J.; Shi, C. Effects of Climatic Factors and Human Activities on Runoff of the Weihe River in Recent Decades. *Quat. Int.* **2012**, *282*, 58–65. [CrossRef]
18. Wei, D.; Liu, S.; Wu, Y.; Feng, S.; Gao, H.; Qin, C.; Ren, D.; Tang, W.; Zhang, Y. Impacts of Human Activities and Climate Change on Water and Sediment Evolution in Four Large Subtropical River Basins in China. *Ecol. Indic.* **2023**, *155*, 110958. [CrossRef]
19. Gao, P.; Li, P.; Zhao, B.; Xu, R.; Zhao, G.; Sun, W.; Mu, X. Use of Double Mass Curves in Hydrologic Benefit Evaluations. *Hydrol. Process.* **2017**, *31*, 4639–4646. [CrossRef]
20. Yin, S.; Gao, G.; Huang, A.; Li, D.; Ran, L.; Nawaz, M.; Xu, Y.J.; Fu, B. Streamflow and Sediment Load Changes from China's Large Rivers: Quantitative Contributions of Climate and Human Activity Factors. *Sci. Total Environ.* **2023**, *876*, 162758. [CrossRef]

21. Xu, X.; Yang, D.; Yang, H.; Lei, H. Attribution Analysis Based on the Budyko Hypothesis for Detecting the Dominant Cause of Runoff Decline in Haihe Basin. *J. Hydrol.* **2014**, *510*, 530–540. [CrossRef]
22. Feng, D.; Zheng, Y.; Mao, Y.; Zhang, A.; Wu, B.; Li, J.; Tian, Y.; Wu, X. An Integrated Hydrological Modeling Approach for Detection and Attribution of Climatic and Human Impacts on Coastal Water Resources. *J. Hydrol.* **2018**, *557*, 305–320. [CrossRef]
23. Jehanzaib, M.; Shah, S.A.; Kwon, H.H.; Kim, T.W. Investigating the Influence of Natural Events and Anthropogenic Activities on Hydrological Drought in South Korea Terrestrial Atmospheric and Oceanic. *Sciences* **2020**, *31*, 85–96.
24. Xue, L.; Yang, F.; Yang, C.; Chen, X.; Zhang, L.; Chi, Y.; Yang, G. Identification of potential impacts of climate change and anthropogenic activities on streamflow alterations in the Tarim River Basin, China. *Science* **2017**, *7*, 8254. [CrossRef]
25. Hu, T.; Toman, E.; Chen, G.; Shao, G.; Zhou, Y.; Li, Y.; Zhao, K.; Feng, Y. Mapping fine-scale human disturbances in a working landscape with Landsat time series on Google Earth Engine. *ISPRS J. Photogramm.* **2021**, *176*, 250–261. [CrossRef]
26. Santikari, V.P.; Murdoch, L.C. Effects of Construction-Related Land Use Change on Streamflow and Sediment Yield. *J. Environ. Manag.* **2019**, *252*, 109605. [CrossRef] [PubMed]
27. Chiang, L.C.; Shih, P.C.; Lu, C.M.; Jhong, B.C. Strategies Analysis for Improving SWAT Model Accuracy and Representativeness of Calibrated Parameters in Sediment Simulation for Various Land Use and Climate Conditions. *J. Hydrol.* **2023**, *626*, 130124. [CrossRef]
28. Briak, H.; Mrabet, R.; Moussadek, R.; Aboumaria, K. Use of a Calibrated SWAT Model to Evaluate the Effects of Agricultural BMPs on Sediments of the Kalaya River Basin (North of Morocco). *Int. Soil Water Conserv.* **2019**, *7*, 176–183. [CrossRef]
29. Fitri, A.; Maulud, K.N.A.; Rossi, F.; Dewantoro, F.; Harsanto, P.; Zuhairi, N.Z. Spatial and Temporal Distribution of Dissolved Oxygen and Suspended Sediment in Kelantan River Basin. In Proceedings of the 4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (ICoSITEA 2020), Yogyakarta, Indonesia, 13–14 October 2021; Volume 199, pp. 51–54.
30. Yang, H.; Shi, C. Spatial and Temporal Variations of Aeolian Sediment Input to the Tributaries (the Ten Kongduis) of the Upper Yellow River. *Aeolian Res.* **2018**, *30*, 1–10. [CrossRef]
31. Yao, H.; Shi, C.; Shao, W.; Bai, J.; Yang, H. Changes and Influencing Factors of the Sediment Load in the Xiliugou Basin of the Upper Yellow River, China. *Catena* **2016**, *142*, 1–10. [CrossRef]
32. Yu, X.; Liu, H.; Wang, Q.; Kou, X.; Cao, X.; Xu, Z.; Wen, L.; Zhuo, Y.; Wang, L. Hydrochemical and Stable Isotope Characteristics of Surface Water and Groundwater in Xiliugou and Wulagai River Basin, North China. *Ecohydrol. Hydrobiol.* **2024**, *24*, 62–72. [CrossRef]
33. Wu, X.; Liu, H.; Guo, X.; Zhang, Z.; Zhang, J.; Huang, X. Microplastic distribution and migration in soil, water and sediments in Caohai Lake under the different hydrological periods, Southwest China. *Sci. Total Environ.* **2023**, *865*, 161292. [CrossRef] [PubMed]
34. CGIAR-CSI. SRTM DEM Dataset in China (2000); A Big Earth Data Platform for Three Poles. 2013. Available online: http://60.245.210.47/en/data/acb49ce8-2bfe-4ab4-97ff-e6e727110703/?q= (accessed on 5 April 2024).
35. Yang, J.; Huang, X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst. Sci. Data* **2021**, *13*, 3907–3925. [CrossRef]
36. Teutschbein, C.; Grabs, T.; Laudon, H.; Karlsen, R.H.; Bishop, K. Simulating Streamflow in Ungauged Basins under a Changing Climate: The Importance of Landscape Characteristics. *J. Hydrol.* **2018**, *561*, 160–178. [CrossRef]
37. White, J.; Walsh, J.; Thoman, R. Using Bayesian Statistics to Detect Trends in Alaskan Precipitation. *Int. J. Climatol.* **2020**, *41*, 2045–2059. [CrossRef]
38. Cai, Y.; Liu, S.; Lin, H. Monitoring the Vegetation Dynamics in the Dongting Lake Wetland from 2000 to 2019 Using the BEAST Algorithm Based on Dense Landsat Time Series. *Appl. Sci.* **2020**, *10*, 4209. [CrossRef]
39. Zhao, K.; Wulder, M.A.; Hu, T.; Bright, R.; Wu, Q.; Qin, H.; Li, Y.; Toman, E.; Mallick, B.; Zhang, X.; et al. Detecting Change-Point, Trend, and Seasonality in Satellite Time Series Data to Tack Abrupt Changes and Nonlinear Dynamics: A Bayesian Ensemble Algorithm. *Remote Sens. Environ.* **2019**, *232*, 111181. [CrossRef]
40. Zhang, Z.; Wang, Z.; Lai, H.; Wang, F.; Li, Y.; Feng, K.; Qi, Q.; Di, D. Lag Time and Cumulative Effects of Climate Factors on Drought in North China Plain. *Water* **2023**, *15*, 3428. [CrossRef]
41. Comiti, F.; Mao, L.; Penna, D.; Dell'Agnese, A.; Engel, M.; Rathburn, S.; Cavalli, M. Glacier melt runoff controls bedload transport in Alpine catchments. *Earth Planet. Sci. Lett.* **2019**, *520*, 77–86. [CrossRef]
42. Van Pelt, W.; Pohjola, V.; Pettersson, R.; Ehwald, L.; Reijmer, C.; Boot, W.; Jakobs, C. Dynamic Response of a High Arctic Glacier to Melt and Runoff Variations. *Geophys. Res. Lett.* **2018**, *45*, 4917–4926. [CrossRef]
43. Yang, W.; Zhang, X.; Wang, Z.; Li, Z. Identifying Components and Controls of Streamflow in a Cold and Arid Headwater Catchment. *J. Hydrol.* **2024**, *633*, 131022. [CrossRef]
44. Wang, Q.; Xia, J.; She, D.; Zhang, X.; Liu, J.; Zhang, Y. Assessment of Four Latest Long-Term Satellite-Based Precipitation Products in Capturing the Extreme Precipitation and Streamflow Across a Humid Region of Southern China. *Atmos. Res.* **2021**, *257*, 105554. [CrossRef]
45. Han, H.; Hou, J.; Huang, M.; Li, Z.; Xu, K.; Zhang, D.; Bai, G.; Wang, C. Impact of Soil and Water Conservation Measures and Precipitation on Streamflow in the Middle and Lower Reaches of the Hulu River Basin, China. *Catena* **2020**, *195*, 104792. [CrossRef]

46. Yang, H.; Shi, C.X.; Cao, J.S. A Field Investigation on Gully Erosion and Implications for Changes in Sediment Delivery Processes in Some Tributaries of the Upper Yellow River in China. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 288. [CrossRef]
47. Wang, H.; Liu, J.; Klaar, M.; Chen, A.; Gudmundsson, L.; Holden, J. Anthropogenic Climate Change Has Influenced Global River Flow Seasonality. *Science* **2024**, *383*, 1009–1014. [CrossRef]
48. Wang, X.L.; Feng, A.Q.; Hou, X.Y.; Chao, Q.C.; Song, B.Y.; Liu, Y.B.; Wang, Q.G.; Xu, H.; Zhang, Y.X.; Li, D.; et al. Compound Extreme Inundation Risk of Coastal Wetlands Caused by Climate Change and Anthropogenic Activities in the Yellow River Delta, China. *Adv. Clim. Chang. Res.* **2024**, *15*, 134–147. [CrossRef]
49. Kuntla, S.K.; Saharia, M.; Prakash, S.; Villarini, G. Precipitation Inequality Exacerbates Streamflow Inequality, But Dams Moderate It. *Sci. Total Environ.* **2024**, *912*, 169098. [CrossRef] [PubMed]
50. Heerspink, B.P.; Kendall, A.D.; Coe, M.T.; Hyndman, D.W. Trends in Streamflow, Evapotranspiration, and Groundwater Storage across the Amazon Basin Linked to Changing Precipitation and Land Cover. *J. Hydrol. Reg. Stud.* **2020**, *32*, 100755. [CrossRef]
51. Shi, M.; Shiraiwa, T. Estimating Future Streamflow Under Climate and Land Use Change Conditions in Northeastern Hokkaido, Japan. *J. Hydrol. Reg. Stud.* **2023**, *50*, 101555. [CrossRef]
52. Lyu, Y.; Chen, H.; Cheng, Z.; He, Y. Identifying the Impacts of Land Use Landscape Pattern and Climate Changes on Streamflow from Past to Future. *J. Environ. Manag.* **2023**, *345*, 118910. [CrossRef]
53. Chu, X.L.; Lu, Z.; Wei, D.; Lei, G.P. Effects of Land Use/Cover Change (LUCC) on the Spatiotemporal Variability of Precipitation and Temperature in the Songnen Plain, China. *J. Integr. Agric.* **2022**, *21*, 235–248. [CrossRef]
54. Zheng, J.; Wang, H.; Liu, B. Impact of the Long-Term Precipitation and Land Use Changes on Runoff Variations in a Humid Subtropical River Basin of China. *J. Hydrol. Reg. Stud.* **2022**, *42*, 101136. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.