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Analysis of the Changes and Causes of Runoff and Sediment Load in the Middle Reaches of the Yellow River from 1950 to 2022

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Abstract: Frequent soil erosion disasters in the middle reaches of the Yellow River (MRYR) have a profound effect on the sediment load of the river. This paper addresses the intertwined effects of human activities and climate change on river runoff and sediment load. Therefore, runoff and sediment loads from hydrological stations along the main and tributary rivers within the MRYR were used. The Mann–Kendall (M–K) trend test and the double mass curve analysis, among other analytical tools, were used to examine the erosion patterns of these rivers from 1950 to 2022, as well as the main factors driving these changes. The results showed that the runoff depth of the Yan River tended to decrease, and there was a significant decrease in the mainstream and nine other tributaries, with a significant decrease in the sediment transport modulus for both the mainstream and tributaries. In the main river, human activities contributed between 69.99% and 94.69% to the runoff and between 88.52% and 98.49% to the sediment load, while in the tributaries, the contribution of human activities was greater. The annual runoff and annual sediment load in the MRYR showed a decreasing trend, with a discernible impact of human activities. The results of this research are of great significance for erosion control and the restoration of the ecological balance in the Yellow River Basin.

Keywords: middle reaches of the Yellow River; runoff; sediment load; contribution

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1. Introduction

Loess is one of the most fertile soils in the world and is crucial for maintaining crop yields on arable land [1]. However, the sensitivity of loess to water and its susceptibility to erosion has led to severe soil erosion [2]. The sediment in the middle reaches of the Yellow River (MRYR) originates mainly from the Loess Plateau, the area where soil erosion is most severe. The Loess Plateau contributes a significant amount of sediment to the Yellow River, resulting in the siltation of downstream reservoirs and riverbeds, as well as the elevation the riverbed [3]. Therefore, a quantitative analysis of the temporal changes in runoff and sediment load in the MRYR is essential for the sustainable management of the basin.

The most commonly used evaluation methods for changes in runoff and sediment load include the runoff and sediment load process line, the cumulative curve method, the Mann–Kendall (M–K) trend test, the ordered cluster analysis, the wavelet analysis, the hydrological model, and others. The study of runoff and sediment load reduction depends on the collection of long-term observational data from river hydrological stations. The dataset includes a range of variables, including river flow, sediment load, precipitation, and other relevant factors [4,5]. Time series analysis represents a fundamental methodology for investigating trends in runoff and sediment load alterations. The M–K trend test may be used to determine the statistical significance of observed changes in runoff and

sediment load levels [6]. Wavelet analysis is a technique that is widely employed for examining both periodic and non-periodic fluctuations in runoff and sediment load time series. This approach allows for the identification of periodic patterns across a range of temporal scales, thereby facilitating a more profound comprehension of the underlying mechanisms governing variations in runoff and sediment load [7]. Physical process-based hydrological models, such as the Variable Infiltration Capacity (VIC) model, are used for the simulation of the hydrological cycle and the assessment of runoff and sediment load under disparate climate scenarios. Such models are capable of incorporating the influences of topography, soil types, vegetation cover, and other factors, thereby facilitating more comprehensive projections of runoff and sediment load [8]. The integrated application of these methodologies allows for a comprehensive evaluation of the status and trends of runoff and sediment load reduction, thus providing a robust tool for elucidating and anticipating the impacts of land-use alteration and climate change on runoff and sediment load reduction.

The reduction in runoff and sediment load is the consequence of a complex interplay between natural and anthropogenic factors. The global water cycle is significantly influenced by climate change, particularly in regard to alterations in precipitation patterns, increases in temperature, and the rise in frequency and intensity of extreme weather events [9,10]. These changes have a cascading effect on runoff and sediment load in river basins. Hovenga et al. [11] investigated the influence of climate change and land use/land cover modification on runoff and sediment load within the Apalachicola River Basin in Florida. The findings of the study indicated that climate change may result in seasonal fluctuations in runoff and sediment load. Additionally, the modelling of land use changes demonstrated that as agricultural and urban areas expand and forested areas diminish, there is an observable increase in sediment load. On the other hand, human activities exert a considerable influence on river runoff and sediment load, primarily through alterations in land cover, increased soil erosion, and modifications to the hydrological cycle and geomorphological processes [12,13]. The construction of dams has a significant impact on downstream hydrological patterns and sediment transport due to their capacity to intercept runoff and sediment load. Van et al. [14] demonstrated that the construction of upstream dams resulted in a notable sediment accumulation, particularly in the Lancang Cascade Dam case. This resulted in a notable decline in sediment loads within the Vietnam Mekong Delta. In addition to the construction of dams, the building of reservoirs and canals can also impact the natural flow of rivers and the distribution of sedimentary materials [15]. Agricultural activities, urbanization, and associated land use changes alter the volume and sediment load of rivers by increasing surface runoff and decreasing infiltration. In the Lower Yazoo River watershed in Mississippi, research has indicated that reforestation can significantly reduce runoff and sediment load [16]. It is also imperative to implement measures for the management of rivers and the conservation of soil and water, including the restoration of vegetation, the management of reservoir sediment, and the construction of river training works. These measures are essential for the mitigation of the impacts of human activities on river systems [17,18]. The Yellow River has experienced a significant reduction in runoff and sediment load as a result of the combined impact of human activities and climate change [19,20]. The construction of check dams in the 1960s and 1970s, the comprehensive management of small catchments in the 1980s and 1990s, and the start of the conversion of farmland back to forest (and grassland) on the Loess Plateau in 1999 have all helped to reduce the sediment load of the Yellow River to historically low levels [21]. Further understanding of the change law of runoff and sediment load in the MRYR is of great significance to the distribution of runoff and sediment load in the MRYR and comprehensive management.

Accordingly, this study is based on the authentic runoff and sediment load data from the principal hydrological stations in the MRYR since 1950. It examines the changes in runoff and sediment load of the mainstream and tributaries in the MRYR, as well as the factors that have caused these changes. The specific objectives of this study are as follows:

(1) to analyze the variation of runoff and sediment load in the MRYR using the M–K trend test, (2) to estimate more precisely the proportion of the reduction in runoff and sediment load attributable to precipitation and human activities, and (3) to analyze the factors affecting runoff and sediment load. The findings of this study may serve as a reference for the formulation of soil and water conservation strategies and the management of areas prone to soil erosion, particularly in other regions facing similar challenges as the Yellow River Basin.

2. Materials and Methods

2.1. Materials

2.1.1. Study Area

The Yellow River originates from the Bayan Har Mountains on the Qinghai–Tibet Plateau, with a total length of approximately 5464 km and a drainage basin area of approximately 795,000 km^2. Most of the river basin is in arid and semiarid regions, with average temperatures ranging between −4 °C and 14 °C and annual precipitation mostly between 200 and 650 mm, while the annual evaporation rate reaches 1100 mm. Based on the geomorphology, geological conditions, and hydrological characteristics of the Yellow River Basin, the river is typically divided into three sections: the upper reaches above Hekou Town, the middle reaches from Hekou Town to Taohuayu, and the lower reaches below Taohuayu, with the major sediment-producing areas predominantly in the middle reaches.

The middle section of the Yellow River stretches from Hekou Town to Taohuayu, encompassing the Longmen (LM) and Tongguan (TG) hydrological stations (Figure 1). The typical tributaries in the MRYR mostly include the Huangfuchuan River, Kuye River, Wuding River, Yan River, Jing River, Beiluo River, Wei River, Fen River, Yiluo River, and Qin River. The corresponding hydrological stations are Huangfu (HF), Wenjiachuan (WJC), Baijiachuan (BJC), Ganguyi (GGY), Zhangjiashan (ZJS), Zhuangtou (ZT), Huaxian (HX), Hejin (HJ), Heishiguan (HSG), and Wuzhi (WZ) (Table 1). In this paper, two major rivers and ten tributary hydrological stations that control runoff and sediment load conditions throughout the middle reaches of the Yellow River Basin were analyzed and studied.

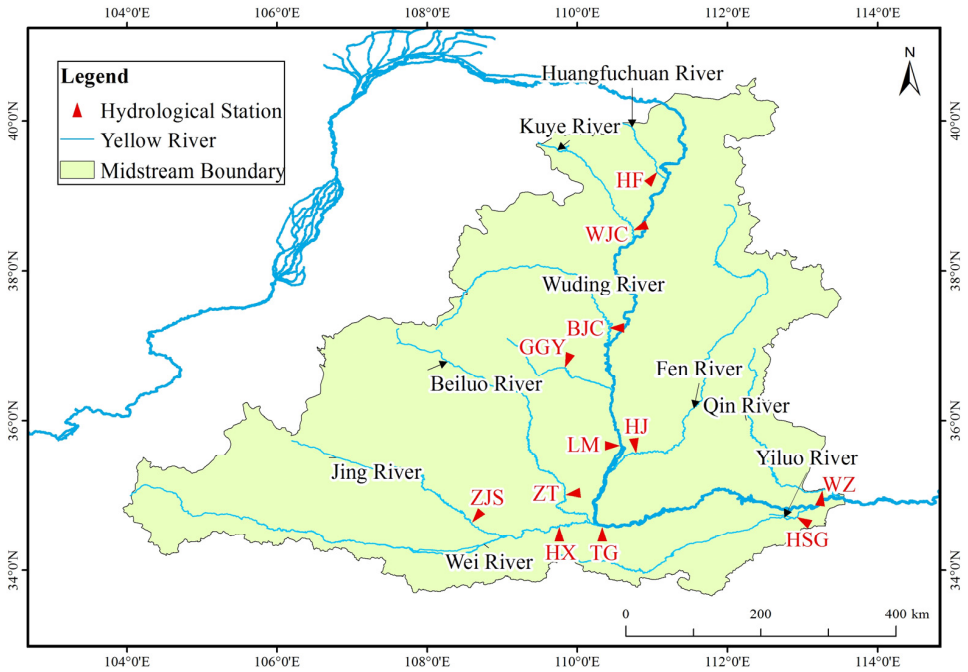


Figure 1. The mainstream of the Yellow River and the hydrological stations at the MRYR: Longmen (LM), Tongguan (TG), Huangfu (HF), Wenjiachuan (WJC), Baijiachuan (BJC), Ganguyi (GGY), Zhangjiashan (ZJS), Zhuangtou (ZT), Huaxian (HX), Hejin (HJ), Heishiguan (HSG), and Wuzhi (WZ).

Table 1. Conditions of the major tributaries of the MRYR.

Tributary Name	Hydrological Station	Data Series (Years)	Drainage Basin Area (km^2)	Mainstream Length (km)
Huangfuchuan River	Huangfu	1954–2022	3199	137
Kuye River	Wenjiachuan	1954–2022	8645	242
Wuding River	Baijiachuan	1956–2022	29,662	491
Yan River	Ganguyi	1952–2022	5891	287
Jing River	Zhangjiashan	1950–2022	43,216	455
Beiluo River	Zhuangtou	1950–2022	25,154	680
Wei River	Huaxian	1950–2022	106,498	818
Fen River	Hejin	1950–2022	38,728	716
Yiluo River	Heishiguan	1950–2022	18,563	447
Qin River	Wuzhi	1950–2022	12,894	485

2.1.2. Data Source

The runoff and sediment load data from hydrological stations were sourced from the China Sediment Bulletin of Rivers, which was published between 1950 and 2022 and included annual runoff and sediment load data. For specific stations, the collection of hydrological data for HF and WJC started after 1954, for BJC, it began in 1956, and for GGY and TG, the collection commenced in 1952. The remaining hydrological stations offer a continuous data set from the outset of 1950 (Table 2). The annual precipitation data were obtained from the National Tibetan Plateau Data Center "http://data.tpdc.ac.cn (accessed on 11 August 2023)". For the period 1962–2022, the precipitation data were based on the China Daily Precipitation Dataset (1961–2022, 0.1°/0.25°/0.5°), and for the period 1952–1961, the precipitation data were supplemented by the China 1 km Resolution Monthly Precipitation Dataset (1901–2022) [22,23]. The former shows good consistency with commonly used precipitation datasets (CGDPA, CN05.1, CMA V2.0), while the latter is validated using data from 496 independent meteorological observation stations, with reliable verification results. Both datasets cover the entire territory of China. The normalized difference vegetation index (NDVI) data for the period of 1981–2000 were sourced from the National Tibetan Plateau Data Center "http://data.tpdc.ac.cn (accessed on 11 August 2023)" using the China Regional Long-Term GIMMS Vegetation Index Dataset (1981–2006) [24]. The vegetation cover data, specifically the fractional vegetation cover (FVC), for the period of 2001–2022 were obtained from the China Regional 250 m Vegetation Cover Dataset (2000–2022) [25], with the latter offering a higher resolution than the former. To obtain the FVC for the summer months (June to August) of the years 1981–2000, the maximum synthesis method was applied to the GIMMS-NDVI data for each month to derive the monthly NDVI for the summer season. Using a pixel binary model, the FVC for the years 1981–2000 was then calculated. Finally, the average value of the summer months (June to August) was taken as the FVC for each corresponding year.

Table 2. Descriptive statistics of runoff and sediment load.

Descriptive Statistics		HF	WJC	BJC	GGY	ZJS	ZT	HX	HJ	HSG	WZ	LM	TG
Runoff (10^8 m^3)	mean	1.2	5.0	10.8	2.0	15.6	7.7	67.5	9.9	25.3	8.0	257.5	334.1
	coefficient of variation (%)	95.51	59.53	30.11	37.26	40.84	37.96	47.00	71.89	64.50	97.07	33.78	35.49
	skewness	1.68	1.01	0.96	1.40	1.24	1.36	1.02	1.30	1.81	1.72	0.77	0.71
	kurtosis	3.12	0.89	0.38	3.08	2.85	3.21	1.60	1.59	4.37	2.65	0.25	0.16
Sediment load (10^8 t)	mean	0.35	0.69	0.92	0.35	1.95	0.63	2.78	0.18	0.10	0.04	6.19	8.90
	coefficient of variation (%)	114.2	120.2	109.0	99.9	75.6	94.4	80.6	180.8	171.1	151.8	88.2	78.9
	skewness	1.57	1.38	1.69	1.74	1.43	1.29	1.45	2.81	3.31	2.33	1.43	1.12
	kurtosis	2.26	1.13	2.28	3.91	1.97	1.27	2.10	9.16	13.83	6.21	1.72	0.82

2.2. Methods

2.2.1. Regarding Physical Quantities

1. Runoff depth (mm)

Runoff depth (R_r) refers to the runoff volume per unit of catchment area discharged in a river basin, reflecting the capacity of the area to generate flow.

$$R_r = \frac{1000W}{A} \tag{1}$$

where is W the runoff volume of a certain year at the hydrological station of the basin, measured in cubic meters (m^3), and A is the catchment area above the cross-section of the hydrological station, measured in square kilometers (km^2).

2. Sediment transport modulus [$t/(km^2 \cdot a)$]

The sediment transport modulus (M) is the amount of sediment transported per unit catchment area in a river basin above a given cross-section and mostly reflects the erosion and sediment production characteristics of the basin.

$$M = \frac{W_s}{A} \tag{2}$$

where W_s represents the annual sediment load at a certain hydrological station cross-section of the river channel, measured in tons per year (t/a), and A is the same as mentioned previously.

2.2.2. Mann–Kendall Trend Test

The M–K trend test [26,27] was primarily used to analyze the annual variation trends of runoff and sediment load. It was performed by calculating the standardized statistical variable U (referred to as the statistic) of a set of hydrological variables and comparing it with the critical values at a certain confidence level (0.05 and 0.002). If $|U| \leq 1.96$, there is no significant change in hydrological volume; if $|U| \geq 3.01$, there is a significant change in hydrological volume; and if $1.96 < |U| < 3.01$, there is a trend in hydrological volume. Additionally, based on the changes observed in different stages, the years of change in runoff and sediment load were identified.

For the given time series:

$$S = \sum_{i=2}^{k} \sum_{j=1}^{i-1} \operatorname{sgn}(x_i - x_j) \quad (k = 2, 3, 4, \cdots, n) \tag{3}$$

$$\operatorname{sgn}(x_i - x_j) = \begin{cases} 1 \, x_i - x_j > 0 \\ 0 \, x_i - x_j \leq 0 \end{cases} \quad (j = 1, 2, 3, \cdots, i-1) \tag{4}$$

$$U = \begin{cases} S - 1/\sqrt{n(n-1)(2n+5)/18} & S > 0 \\ 0 & S = 0 \\ S + 1/\sqrt{n(n-1)(2n+5)/18} & S < 0 \end{cases} \tag{5}$$

where S is the cumulative count of the number of times each value is in the sequence x_2, x_3, …, x_k is greater than the value at the preceding moment, and U is the statistic of the standard normal distribution.

2.2.3. Double Mass Curve Analysis

Using data from before the critical year, two cumulative curve equations were constructed to describe the relationships between precipitation and runoff and between precipitation and sediment load. After the critical year, the precipitation data were input into these two regression equations to obtain the simulated runoff and sediment load values for

the intervention period. Finally, the following formulas were used to determine the impact of precipitation and human activities on runoff and sediment load volume [28,29]:

$$W_1 = R_z - R_j \tag{6}$$

$$W_2 = R_s - R_z \tag{7}$$

$$C_1 = W_2 / W_1 \tag{8}$$

$$C_2 = (W_2 - W_1) / W_1 \tag{9}$$

where W_1 represents the changes in runoff/sediment load volume under the combined effects of climate change and human activities. W_2 represents the changes in runoff/sediment load volume due to non-climatic factors. R_z is the average measured runoff/sediment load volume during the intervention period. R_j is the average measured runoff/sediment load volume during the baseline period. R_s is the average calculated runoff/sediment load volume during the intervention period. C_1 indicates the extent of the impact of human activities on the changes in runoff/sediment load volume. C_2 represents the impact of precipitation changes on the changes in runoff/sediment load volume.

2.2.4. Trend Analysis Method

Using the trend analysis method to analyze the changes in the FVC within the study area, the calculation formula is as follows:

$$Slope = \frac{n \times \sum_{i-1}^{n} i \times FVC_i - \sum_{i=1}^{n} i \sum_{i-1}^{n} FVC_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i-1}^{n} i \right)^2} \tag{10}$$

where n represents the number of study periods, i represents the year of study, and FVC_i represents the NDVI value of the i-th year. A slope greater than 0 indicates that FVC for that pixel is increasing; a slope equal to 0 indicates that the FVC for that pixel remains essentially unchanged; and a slope less than 0 indicates that the FVC for that pixel is decreasing.

3. Results

3.1. Runoff and Sediment Load Variation

3.1.1. Runoff Variation

The runoff depth mainly reflects the capacity of the MRYR to produce flow, and the changes in flow production in the basin were explored through changes in runoff depth. Table 3 illustrates the annual variation in runoff depth in the tributaries of the middle reaches of the Yellow River, including the results of the M–K trend test, and outlining the decay pattern, while Figure 2 presents the M–K curve for runoff depth. This can be seen in Table 3 and Figure 2.

1. The runoff depths at LM and TG were 51.75 mm and 48.97 mm, respectively, and their M–K test values were −4.486 and −4.840, respectively. These values continuously decreased from 1969 to 1997, with little change after 1997 and a slight upward trend after 2010, indicating that the runoff depths at these two hydrological stations significantly decreased.
2. The runoff depth of the Yiluo River was greater, with an average value of 136.2 mm for many years, and the M–K test value was of −4.524, indicating that the runoff depths of this tributary exhibited a significant decreasing trend and that its flow production capacity was significantly weakened. The Yiluo River decreased significantly after 1965 and 1985, with mean values of 220.32 mm, 141.25 mm, and 97.01 mm, respectively, for the three periods.
3. The runoff depths of the MRYR in the Kuye River, Wei River, and Qin River were small, with a variation interval of 55–65 mm, corresponding to a weakening of flow

production capacity. The M–K test values were −6.371, −3.210, and −4.248, respectively, indicating that the runoff depths of the three tributaries significantly decreased from 95.23 mm, 80.31 mm, and 123.23 mm in the 1950s to 26.95 mm, 53.46 mm, and 45.79 mm in the 2000s, respectively.

4. The runoff depths of the Huangfuchuan River, Wuding River, Yan River, Jing River, Beiluo River, and Fen River in the MRYR were very small, with multiyear averages ranging from 25 to 40 mm, indicating very weak flow-producing capacity. The values of their M–K statistics were −6.526, −6.878, −2.864, −3.438, −3.048, and −4.515, indicating that the runoff depths of the Yan River and Beiluo River tended to decrease, while those of the remaining four tributaries decreased significantly.

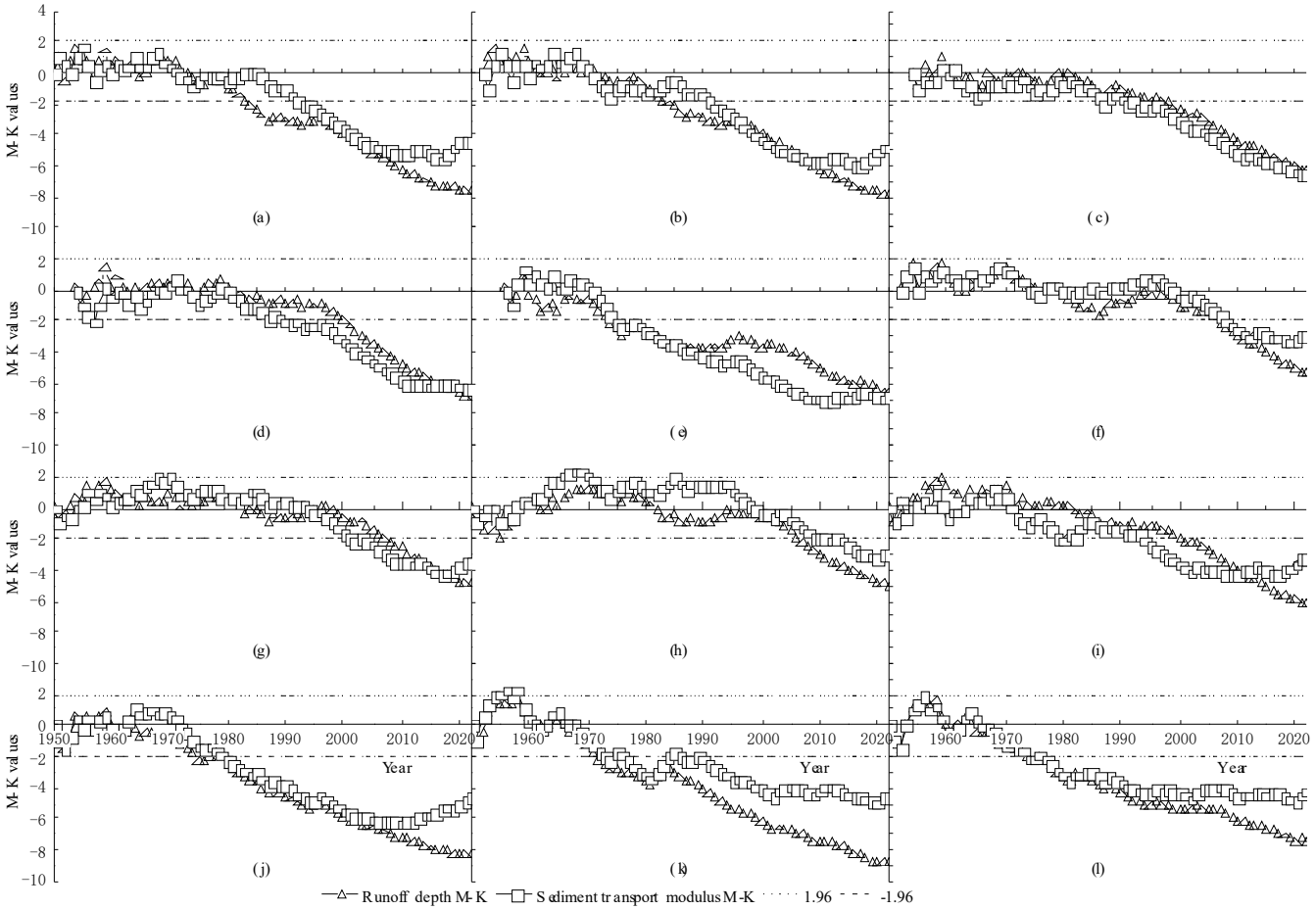


Figure 2. M–K curves of runoff depth/sediment transport modulus at main and tributary major hydrological stations in MRYR: (**a**) LM, (**b**) TG, (**c**) Huangfu (Huangfuchuan River), (**d**) Wenjiachuan (Kuye River), (**e**) Baijiachuan (Wuding River), (**f**) Ganguyi (Yan River), (**g**) Zhangjiashan (Jing River), (**h**) Zhuangtou (Beiluo River), (**i**) Huaxian (Wei River), (**j**) Hejin (Fen River), (**k**) Heishiguan (Yiluo River), (**l**) Wuzhi (Qin River).

Table 3. Variations in runoff depth and sediment transport modulus in the main and tributary streams of the MRYR and the M–K trend test results.

	Year	Huangfuchuan River	Kuye River	Wuding River	Yan River	Jing River	Beiluo River	Wei River	Fen River	Yiluo River	Qin River	Mainstream	
		HF	WJC	BJC	GGY	ZJS	ZT	HX	HJ	HSG	WZ	LM	TG
Runoff depth (mm)	1950–1959	82.95	95.23	53.34	36.29	37.58	28.87	80.31	45.36	217.39	123.23	61.48	62.69
	1960–1969	53.86	85.09	51.29	42.08	50.15	40.22	90.31	46.13	191.11	108.84	67.65	66.11
	1970–1979	54.94	83.58	40.81	35.01	40.38	33.21	55.79	26.77	110.21	47.68	57.19	52.39
	1980–1989	39.74	60.20	34.93	35.33	39.62	36.63	74.30	17.17	162.46	42.39	55.51	54.10
	1990–1999	28.23	51.85	31.50	35.22	32.42	28.25	41.12	13.13	78.40	28.93	39.82	36.47
	2000–2009	11.27	19.54	25.43	24.91	23.07	24.72	42.29	9.02	93.46	41.26	34.26	30.85
	2010–2019	9.16	35.21	30.18	26.23	27.33	22.55	52.79	17.91	93.71	29.00	45.70	41.09
	2020–2022	7.52	24.15	27.95	34.74	41.64	30.95	86.23	33.99	158.45	112.03	53.78	55.15
	Multiyear average	36.12	57.95	36.40	33.55	36.03	30.65	63.39	25.44	136.20	62.32	51.75	48.97
	M–K trend test (U)	−6.526	−6.371	−6.878	−2.864	−3.438	−3.048	−3.210	−4.515	−4.524	−4.248	−4.5	−4.8
	Abrupt change year	1980 1996	1980 1996	1972 1996	1970 1996	1970 1996	1970 1994	1968 1993	1971	1965 1990	1964 1982	-	-
Sediment transport modulus [t/(km^2·a)]	1950–1959	24,394	15,666	10,021	8888	6273	4157	4027	1807	1938	1032	2390	2677
	1960–1969	15,768	13,705	6293	10,791	6262	4076	4095	888	974	564	2274	2086
	1970–1979	19,547	16,178	3910	7948	6007	3531	3607	494	371	316	1745	1932
	1980–1989	13,386	7757	1777	5418	4313	1999	2590	116	477	194	945	1144
	1990–1999	7974	7490	2834	7275	5491	3534	2595	82	50	70	1023	1158
	2000–2009	3007	600	1219	2879	2588	883	1294	8	39	73	356	455
	2010–2019	1110	110	691	776	1455	363	620	6	16	10	253	260
	2020–2022	427	19	481	583	1733	374	695	10	65	109	300	300
	Multiyear average	10,950	8007	3116	5968	4508	2510	2608	466	532	314	1243	1305
	M–K trend test (U)	−6.412	−7.023	−6.521	−5.366	−4.991	−5.096	−6.201	−8.353	−8.934	−7.486	−7.75	−7.93
	Abrupt change year	1979 1996	1979 1996	1971 1996	1971 1996	1971 1997	1979 2002	1971 1996	1971	1964 1984	1964 1982	-	-

3.1.2. Sediment Load Variation

Table 3 illustrates the annual variation and the M–K trend test results for the sediment transport modulus in the main and tributary streams of the MRYR, as well as the decay pattern, while Figure 2 presents the M–K curve for the sediment transport modulus. From Table 3 and Figure 2, the following can be observed:

1. The sediment transport modulus at LM and TG were 1243.31 t/(km^2·a) and 1305.40 t/(km^2·a), respectively, and their M–K test values were −7.753 and −7.927, respectively, which indicates that the sediment transport modulus at these two hydrological stations decreased significantly.
2. The sediment transport modulus of the Fen River, Yiluo River, and Qin River was relatively small, with the average value over many years being less than 550 t/(km^2·a). The watershed erosion was relatively low, and the M–K test value was between −8.934 and −7.486, which indicates that these tributaries reduced the sediment transport modulus and that watershed erosion weakened, though the erosion change processes varied. The sediment transport modulus of the Fen River clearly and continuously decreased from 1960 to 1980, while the sediment transport modulus of the Qin River and Yiluo River showed a continuous decreasing trend, from 1938 t/(km^2·a) and 1032 t/(km^2·a) in the 1950s to 32.81 t/(km^2·a) and 26.94 t/(km^2·a) after 2010, respectively.
3. The sediment transport modulus of the Huangfuchuan River, Kuye River, and Yan River was very high, indicating severe erosion of the basin. The annual average values were as high as 10,950 t/(km^2·a), 8007 t/(km^2·a), and 5968 t/(km^2·a), respectively, and their M–K test values were −6.412, −7.023, and −5.366, respectively. The corresponding accumulation process lines were convex, indicating that the sediment transport modulus of these three tributaries was significantly reduced. After 2010, the sediment transport modulus decreased from 24,394 t/(km^2·a), 15,666 t/(km^2·a), and 8888 t/(km^2·a) in the 1950s to 952.22 t/(km^2·a), 89.98 t/(km^2·a), and 731.10 t/(km^2·a), respectively. The erosion characteristics of the basins gradually changed from severe erosion to weak erosion.
4. The sediment transport modulus of the Wuding River, Jing River, Beiluo River, and Wei River were between 2500 and 5000 t/(km^2·a), with the M–K test values of −6.521, −4.991, −5.096, and −6.201, respectively, indicating that the sediment transport modulus of these four tributaries significantly decreased. The sediment transport modulus of the Jing River, Beiluo River, and Wei River decreased continuously from the 1980s, while the sediment transport modulus of the Wuding River decreased sharply from 10,021 t/(km^2·a) in the 1950s to 3910 t/(km^2·a) in the 1970s and then to 642.37 t/(km^2·a) after 2010. The erosive characteristics of these tributaries gradually changed from more severe to less severe.

3.2. Proportion of Runoff and Sediment Load Reduction Attributed to Precipitation and Human Activities

3.2.1. Mainstream

For the mainstream of the MRYR, the difference in data between the two hydrological stations, Toudaoguai and TG, was first used to determine the annual runoff and sediment load of the mainstream of the MRYR. The M–K trend test was then applied to conduct abrupt change tests on the annual runoff and sediment load. The results indicated abrupt changes in runoff volume between 1985 and 1994 and in sediment load between 1979 and 1996.

Double cumulative curves for precipitation–runoff and precipitation–sediment load were generated (Figure 3), and the roles of precipitation and human activities in reducing runoff and sediment load were calculated based on theoretical and recorded values (Table 4). The slopes of the precipitation–runoff and precipitation–sediment load double cumulative curves in the MRYR decrease at each turning point, indicating that, under the same amount of precipitation, both the runoff and sediment load are decreasing. In the MRYR from 1986

to 1994, the runoff volume decreased by 4.953 billion m^3 compared to the period before the abrupt change, with human activities contributing more (69.99%) than precipitation (30.01%), indicating that human activities were more dominant. Similarly, from 1995 to 2022, the runoff volume decreased by 8.480 billion m^3, with human activities contributing significantly more (94.69%) than precipitation (5.31%). Between 1980 and 1996, the sediment load decreased by 604 million t compared to the period from 1952 to 1979, with human activities accounting for approximately 88.52% of this reduction. Furthermore, from 1997 to 2022, the sediment load decreased by 1125 million t, with human activities accounting for approximately 98.49% of the reduction. Thus, human activities were identified as the primary cause of the decrease in sediment load within the river basin.

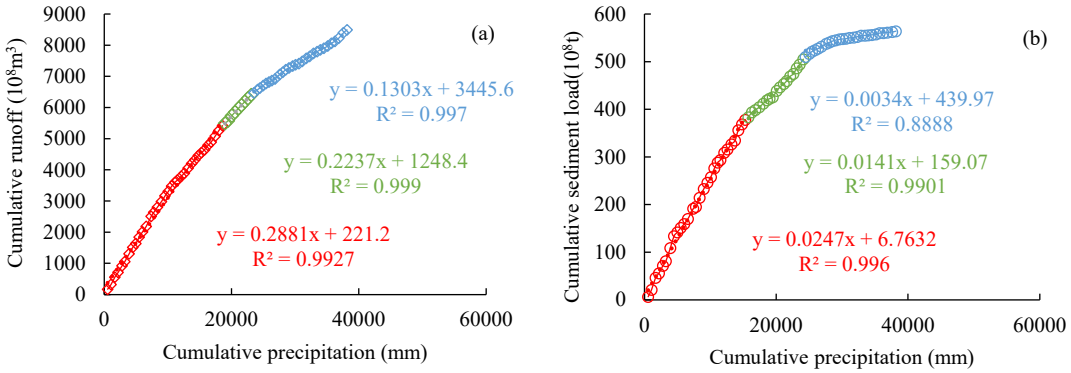


Figure 3. Double cumulative curves of precipitation–runoff and precipitation–sediment loads in the MRYR mainstream. (**a**) Precipitation–runoff load; (**b**) precipitation–sediment load.

Table 4. The impact of human activities and precipitation changes on runoff and sediment load in the MRYR mainstream.

	Time Period	Computed Values	Measured Values	Reduce the Total Values	Human Activities		Precipitation	
					Affected Values (10^8 m^3)	Contribution (%)	Affected Values (10^8 t)	Contribution (%)
Runoff	1952–1985	157.53	159.37					
	1986–1994	144.51	109.84	49.53	34.66	69.99	14.86	30.01
	1995–2022	154.87	74.58	84.80	80.29	94.69	4.50	5.31
Sediment Load	1952–1979	13.49	13.51					
	1980–1996	12.82	7.47	6.04	5.35	88.52	0.69	11.48
	1997–2022	13.34	2.27	11.25	11.08	98.49	0.17	1.51

3.2.2. Tributaries

The M–K trend test was applied to determine the abrupt change point years for each tributary, and a double cumulative curve was fitted to calculate the contributions of human activities and precipitation to the reduction in runoff. From Table 1, it can be observed that, except for the Fen River, which had only one abrupt change point in 1971, the first abrupt change point for the other tributaries occurred between 1964 and 1980. The earliest second abrupt change point occurred in 1982 for the Qin River, and the latest abrupt change points occurred in 1996 for the Huangfuchuan River, Kuye River, Wuding River, Yan River, and Jing River. Based on these abrupt change points, each tributary was divided into three periods: the baseline period, the first intervention period (period I), and the second intervention period (period II). Overall (Table 5), the contribution of human activities to the tributaries was significantly greater than that of precipitation. Relative to the baseline period, during the first intervention period (period I) for each tributary, the contribution of human activities to runoff changes was mostly within the range of 40% to 90%, while the impact of precipitation factors on runoff changes was mostly between 8% and 60%. Relative

to period I, the proportion of contributions from human activities increased significantly in the second intervention period (period II), averaging 88.64%, which was also significantly greater than the contribution of precipitation factors (11.36%).

Table 5. The impact of human activities and precipitation changes on runoff and sediment load of different tributaries.

River Basin Name	Time Period	Runoff				Sediment Load			
		Human Activity		Precipitation		Human Activity		Precipitation	
		Affected Values (10^8 m^3)	Contribution (%)	Affected Values (10^8 m^3)	Contribution (%)	Affected Values (10^8 t)	Contribution (%)	Affected Values (10^8 t)	Contribution (%)
Huangfuchuan River	Period I	0.43	55.46	0.35	44.54	0.16	66.33	0.08	33.67
	Period II	1.36	84.93	0.24	15.07	0.50	91.82	0.04	8.18
Kuye River	Period I	1.52	65.13	0.81	34.87	0.46	80.06	0.11	19.94
	Period II	4.8	94.07	0.3	5.93	1.24	98.22	0.02	1.78
Wuding River	Period I	2.55	55.19	2.07	44.81	0.99	72.90	0.37	27.10
	Period II	6.23	88.38	0.82	11.62	1.66	89.21	0.20	10.79
Yan River	Period I	−0.01	−7.95	0.2	107.95	0.14	82.78	0.03	17.22
	Period II	0.67	89.26	0.08	10.74	0.48	100.01	0	−0.01
Jing River	Period I	1.05	40.25	1.55	59.75	0.28	58.69	0.19	41.31
	Period II	6.85	90.16	0.75	9.84	1.83	99.52	0.01	0.48
Beiluo River	Period I	−0.66	305.91	0.45	−205.91	0.21	86.98	0.03	13.02
	Period II	2.4	92.9	0.18	7.1	0.90	109.16	−0.08	−9.16
Wei River	Period I	18.58	73.23	6.79	26.77	1.06	76.36	0.33	23.64
	Period II	34.34	81.94	7.57	18.06	3.15	93.22	0.23	6.78
Fen River	Period I	9.86	90.88	0.99	9.12	0.42	89.61	0.05	10.39
Yiluo River	Period I	14.27	91.17	1.38	8.83	0.26	113.21	−0.03	−13.21
	Period II	21.39	91.41	2.01	8.59	0.33	106.82	−0.02	−6.82
Qin River	Period I	8.16	80.8	1.94	19.2	0.08	98.48	0	1.52
	Period II	9.93	84.7	1.79	15.3	0.11	100	0	0

Similarly, the abrupt change point years for the tributaries were determined, along with the contributions of human activities and precipitation to the reduction in sediment load. Table 1 shows that, except for the Fen River, which had only one abrupt change point in 1971, the first abrupt change point for the other tributaries occurred between 1964 and 1979, and the second abrupt change point occurred between 1982 and 2002. Based on these abrupt change points, the time was divided into the baseline period, the first intervention period (period I), and the second intervention period (period II). There was a greater proportion of human activities in sediment load than in runoff, which was high in both intervention periods I and II. In the intervention period I, the average was 82.54%, and in the intervention period II, it was higher, averaging 98.66%. The proportion of sediment load reduction attributed to precipitation was 17.46% for the intervention period I and 1.34% for the intervention period II (Table 5).

From this, it can be inferred that human activities were the main factor contributing to the sharp decrease in runoff and sediment load in the MRYR tributaries during different periods, with a greater proportion in the intervention period II.

4. Discussion

4.1. Changes in Influencing Factors

The major factors influencing changes in runoff and sediment load in the MRYR were human activities and precipitation changes, with human activities being dominant. These factors include soil and water conservation measures, sediment load trapping by reservoirs, and runoff and sediment load diversion projects [30,31].

4.1.1. Precipitation

Generally, the volume of runoff and sediment load a river naturally carries is directly proportional to the precipitation in its watershed, with a decrease in precipitation leading to reduced river runoff and subsequently a decrease in sediment load [32,33]. First, an analysis of the M–K trend test for the multiyear average precipitation in the MRYR was conducted, with the M–K test value being 0.144, indicating an increasing trend in the

multiyear precipitation. Second, based on previous research [2,34], the years 1979 and 1996 were selected as dividing points. For the mainstream of the MRYR, the differences in annual runoff and sediment load between the Toudaoguai and TG hydrological stations, along with the annual precipitation in the MRYR, were used to establish the relationship curves between annual precipitation and runoff depth, as well as between annual precipitation and the sediment transport modulus for the mainstream (Figure 4). Although there was a good positive correlation between runoff depth and precipitation, the correlation between the sediment transport modulus and precipitation was not evident. Moreover, since 1997, there has been a decreasing trend in the sediment transport modulus relative to precipitation, which may be attributed to the impact of reservoir water storage and sediment load trapping.

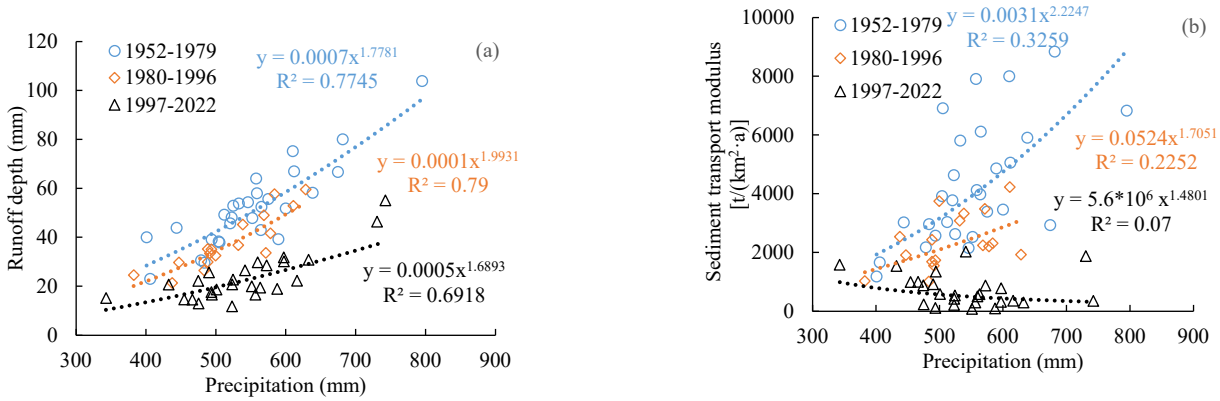


Figure 4. Relationship between runoff and sediment load values and precipitation in the MRYR (Toudaoguai-TG). (**a**) Runoff depth; (**b**) sediment transport modulus.

4.1.2. Soil and Water Conservation Measures

As a major area for soil and water conservation in the Yellow River Basin, the MRYR has implemented a series of soil and water conservation measures, including both biological and engineering measures. These measures include returning farmland to forests and grasslands, constructing soil and water conservation projects, and afforestation. Soil and water conservation work efforts have been carried out in the MRYR and the Loess Plateau since the 1960s. The area of soil and water conservation has been rapidly increasing, from 15,800 km^2 and 7000 km^2 in the 1960s to 171,300 km^2 and 62,600 km^2 in the 1990s, respectively. From 2010 to 2015, the area of soil and water conservation on the Loess Plateau increased to 124,600 km^2 [35,36].

(1) Biological measures. Since the implementation of the Grain for Green project in 1999, the ecological environment in the MRYR has improved. Therefore, with the year 2000 as the dividing point, a continuous time series slope trend analysis of the FVC (from June to August) was conducted using the ArcGIS 10.2 raster calculator. This analysis was based on the classification method of previous studies [37], which categorized the changes in the FVC into seven types (Table 6). Finally, by comparing the rates of change in the FVC, the vegetation changes in the MRYR from 1981 to 2022 were analyzed.

Figure 5 shows that from 1981 to 2022, the FVC exhibited an overall increasing trend, with different patterns of change observed in the two respective periods. In general, before the change (from 1981 to 2000), the proportion of the FVC that showed an increasing trend was 50.17%, while after the change (from 2001 to 2022), this proportion increased to 93.73%. Additionally, in terms of the degree of change (Table 6), before the change, the vegetation was primarily characterized by slight improvement and no significant change, accounting for 73.05%. However, after the change, the vegetation showed a shift towards moderate improvement and significant improvement, with percentages of 21.69% and 52.38%, respectively. From 1981 to 2000, the greatest changes in the FVC were observed in the Huangfuchuan River Basin and the Hekou Town to the LM mainstream section.

Moreover, a downward trend in the FVC was noted in parts of the middle reaches of the Fen River, the lower reaches of the Qin River, the lower reaches of the Yan River, and the upper reaches of the Wei River. After 2001–2022, the large-scale conversion of cultivated land to forests and grasslands led to a significant increase in the FVC. Among these areas, the FVC in the Hekou Town to the LM section exhibited the most pronounced increase, especially in most areas of the Jing River. However, the increase in the FVC for the Qin River and Yiluo River was relatively slow.

Table 6. Classification of FVC levels based on slope values.

Slope Value	The Extent of Change	Area Proportion (%)	
		1981–2000	2001–2022
<−0.01	Significant degradation	1.02	0.28
−0.01~−0.005	Moderate degradation	9.61	0.92
−0.005~−0.001	Mild degradation	29.31	2.37
−0.001~0.001	Stable	20.60	7.13
0.001~0.005	Slight improvement	23.15	15.23
0.005~0.01	Moderate improvement	12.39	21.69
>0.01	Significant improvement	3.93	52.38

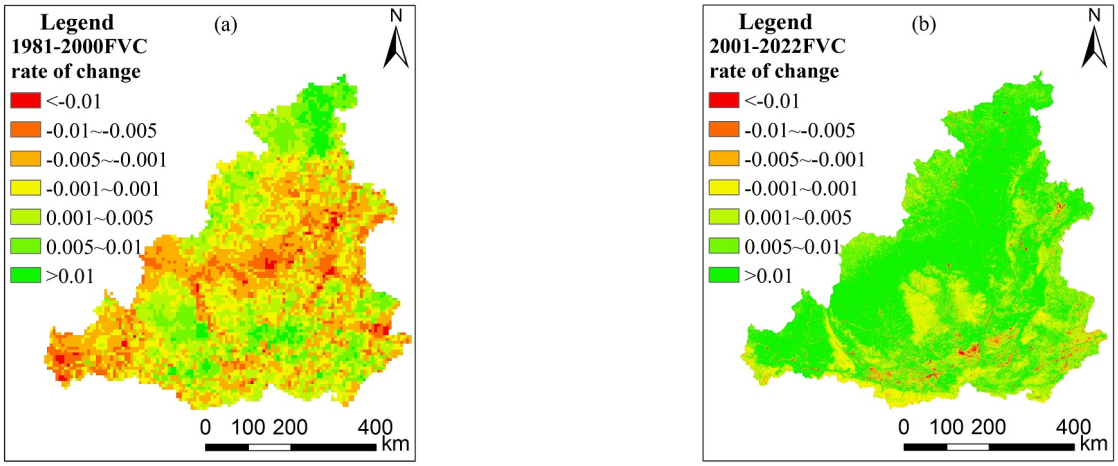


Figure 5. FVC variation levels in MRYR. (**a**)1981–2000 FVC rate of change; (**b**) 2001–2022 FVC rate of change.

(2) Engineering measures. The engineering measures in the MRYR mostly included terraces and check dams, which more directly impacted sediment load reduction. The construction peak of large-scale check dams in the MRYR occurred from 1970 to 1979 and from 2000 to 2009. Taking the Wuding River as an example, in 1980, there were 4745 check dams with available storage capacity. By 1999, there were 9455 check dams that had intercepted 1.73 billion m^3 of sediment load. Between 2003 and 2007, 663 check dams were constructed (data source: "National Cryosphere Desert Data Center"), which greatly enhanced the ability to intercept sediment load deposition [38–40].

4.1.3. Reservoir Sediment Interception

The construction of reservoirs in the MRYR began in 1956, with the most concentrated period occurring in the 1970s and 1980s. The number of reservoirs built between the 1980s and 2000 was relatively low, but there has been an increase in reservoir construction since the 21st century. There are 15 typical reservoirs in the MRYR, with a total storage capacity of 53.163 billion m^3. The designed storage capacities of the Wanjiazhai and Longkou reservoirs are 8.96 and 1.96 billion m^3, respectively. During the 2022 flood season, the Wanjiazhai reservoir experienced a sediment load inflow of 0.0405 billion t and a sediment

load outflow of 0.3278 billion t. Additionally, the Longkou reservoir had a sediment load outflow of 0.4557 billion t (data source: "Yellow River Sediment Bulletin"). As illustrated in Figure 6, the year when the sediment load at TG began to decrease sharply corresponded with the year when large backbone reservoirs were constructed and put into operation on the river. These reservoirs control runoff and sediment load processes and quantities, regulate the intra-annual runoff process, intercept a large amount of sediment load, reduce the sediment load exiting the reservoir, and noticeably transform the runoff and sediment load processes that enter downstream river channels (data source: "China Water Statistical Yearbook 2020") [41].

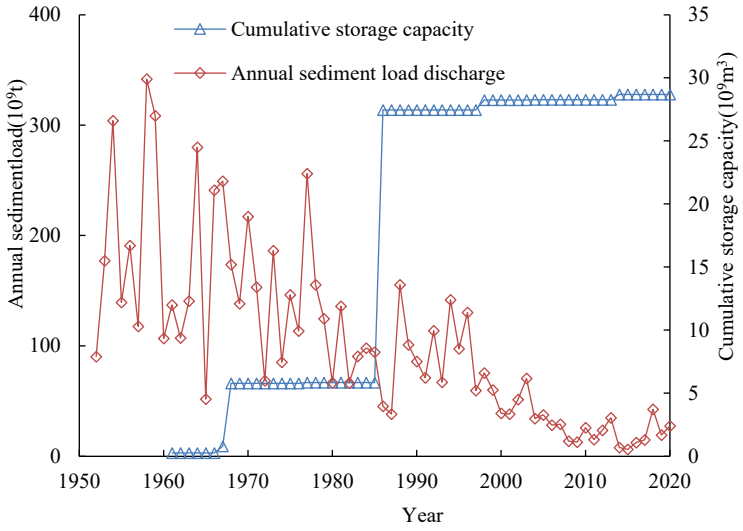


Figure 6. Sediment load at TG and cumulative storage capacity.

4.1.4. Water Diversion and Sediment Load Diversion

With the continuous development of socioeconomic and agricultural production, the scale of water diversion from rivers has been gradually increasing. This encompasses several areas: agricultural irrigation, water for industrial purposes, water for ecological uses, and water for domestic use in both urban and rural settings. An analysis of water intake and consumption from 1998 to 2022 (excluding 2018) in the Toudaoguai to LM hydrological stations of the MRYR is shown in Figure 7. Both the multiyear average water intake and consumption show an increasing trend, with an average water intake of 17.55 billion m^3 and an average water consumption of 14.583 billion m^3 (data source: "Yellow River Water Resources Bulletin"). When the water is diverted, the sediment load is also diverted. To further analyze the changes in the sediment load in the middle reaches, by utilizing the annual average sediment load content data from Toudaoguai and LM hydrological stations, one can determine the sediment load (as shown in Figure 7). The annual average sediment load associated with water intake was calculated to be 89.62 million t, and the annual average sediment load associated with water consumption was 75.34 million t. Moreover, there has been an increasing trend in the sediment load over the past ten years [42].

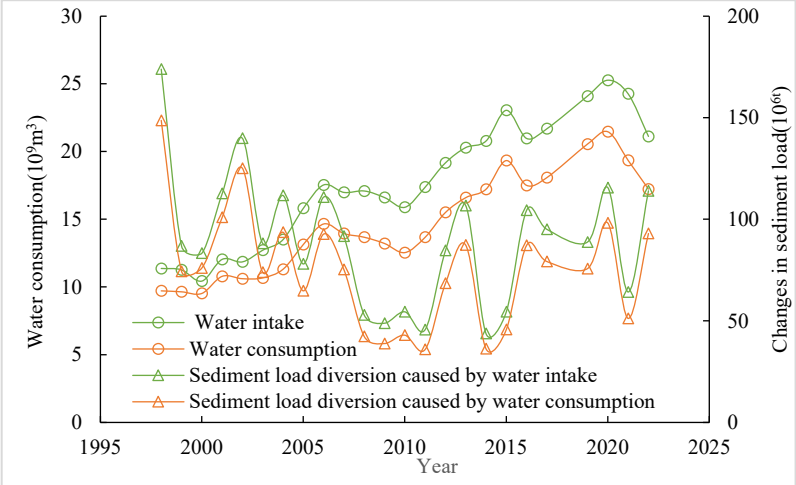


Figure 7. Changes in water intake and consumption and the corresponding sediment load diversion volumes in the MRYR from 1998 to 2022.

4.2. Analysis of Runoff and Sediment Load Changes and Identification of Abrupt Change Points

4.2.1. Evaluation of the Trend and Identification of Abrupt Change Points in the Runoff and Sediment Load Changes

Common methods used for trend analysis and identification of abrupt changes in runoff and sediment load in the Yellow River include the moving average method, the cumulative deviation method, the double cumulative curve method, the M–K trend test, and the Pettitt test. However, each of these methods has its own advantages and disadvantages. The commonly used moving average method can eliminate periodic and random fluctuations in runoff and sediment load variations, making the data smoother. However, this smoothing can obscure the identification of abrupt changes, making these points subject to human factors, and outliers can greatly impact the results of the moving average [43]. The M–K trend test primarily shows that the samples do not have to follow a pattern, showing less influence from human factors. However, in terms of computational results, the M–K trend test often identifies multiple abrupt change points. To address the issue of multiple abrupt change points, methods such as the Pettitt test, the double cumulative curve method, and the cumulative deviation method are commonly used. Gao et al. [44] applied the M–K method to test for trends and the Pettitt test to analyze abrupt changes at four Yellow River hydrological stations: Tangnaihai, Toudaoguai, Huayuankou, and Lijin. They found that the runoff and sediment load in most areas of the Yellow River Basin began to decline in 1985. Scholars have identified abrupt change points in the MRYR since the 1970s. Similarly, in this study, using the M–K trend test for the mainstream of the MRYR, the abrupt change points for runoff and sediment load were identified as 1985, 1994, 1979, and 1996. For the tributaries, the abrupt changes occurred after the 1960s. Although there are some differences in the abrupt change points, the basic conclusions are consistent.

4.2.2. Differences in the Abrupt Change Points of Runoff and Sediment Load

Human activities, including the construction of reservoirs, water diversion, and terracing, have directly or indirectly affected the annual runoff in the MRYR. Zhou et al. [45] employed seven time series analysis methods to ascertain that the annual runoff of the Wuding River underwent abrupt changes in 1971 and 1997. These changes were found to be closely related to human activities, specifically the implementation of large-scale soil and water conservation measures in 1971 and the subsequent implementation of ecological restoration projects in 1997. In this study, there were two abrupt change points of abrupt change in both the runoff and sediment load of the mainstream of the Yellow River. The first abrupt change in annual sediment load occurred in 1979, which was earlier than the change in annual runoff in 1985, with the direct cause being the large-scale construction of reser-

voirs before 1980 [34]. The second abrupt change occurred after the point of change in the annual runoff, which may be attributed to the lag effect of the conversion of farmland back to forest policy [29] (Table 5). In contrast to the prevailing trend observed in mainstream rivers, tributaries such as the Huangfuchuan River, Kuye River, Wuding River, Yan River, Jing River, Fen River, and Qin River exhibit a relatively consistent pattern in the abrupt change points of abrupt change in annual runoff and sediment load. However, in the case of the Beiluo River and Wei River, the two abrupt change points of abrupt change in annual sediment load occurred later than those for annual runoff. This can be attributed to similar factors affecting the mainstream. In contrast, the second point of abrupt change in the annual runoff of the Yiluo River (1990) occurred later than the change in annual sediment load (1984) due to the impact of climate change [46]. It is evident that the differences in the abrupt change points of the mainstream and major tributaries in the MRYR are related to specific human activities and changes in climatic conditions.

4.2.3. Comparison of the Differences in the Assessment Results

Methods such as the 'hydrological method', the 'soil and water conservation method', and model simulation are commonly used to analyze the contributions of influencing factors to changes in runoff and sediment load. However, when using multiple methods for calculation, discrepancies in the results often occur. For example, Wang et al. [47] used the cumulative slope method, the hydrological method, and the soil and water conservation method to compare and analyze the driving factors of changes in runoff and sediment load in the Ningxia section of the Yellow River. The results from the cumulative slope method and the hydrological method are more consistent with each other, while the soil and water conservation methods show a greater contribution rate to runoff changes. In terms of sediment load, the contribution rate of human activities is similar to that obtained by the cumulative slope method. In this paper, the double cumulative curve method was applied to the mainstream of the MRYR, considering only precipitation as a single independent variable. Factors such as the lag of sediment load reduction, the continuous implementation of management measures, and the uneven distribution of precipitation throughout the year were not considered. As a result, the contribution of human activities to the changes in runoff and sediment load was underestimated in the findings. Additionally, there were instances where the calculated contribution rate of human activities exceeded 100%. This is because the error gradually accumulated and increased during the calculation process.

Although scholars have varying opinions regarding the contribution rates of influencing factors to changes in runoff and sediment load during different periods, the consensus on the contribution rates to changes in runoff and sediment load in the MRYR is generally consistent (Table 7). That is, since 2000, the contribution rate of human activities has been greater than that of precipitation. In recent years, the role of precipitation in reducing runoff and sediment load has diminished considerably, while the impact of human activities has increased markedly.

Table 7. Partial research findings on the contribution rates of precipitation and human activity to the reduction in runoff and sediment load in the MRYR.

References	Study Area	Data Range	Research Methods	Runoff Reduction Contribution Proportion (%)		Sediment Load Reduction Contribution Proportion (%)	
				Human Activities	Precipitation	Human Activities	Precipitation
Liu et al. [48]	LM-TG Hydrological Stations	1957~2019	Double Cumulative Quantity Slope Change Rate Comparison Method	73.79	26.20	77.2~88.27	11.73~22.8
Zhao et al. [49]	Lanzhou-TG Hydrological Stations	1950~2016	Double Cumulative Curve Method	88.90	11.10	91.82	8.18
Yao et al. [50]	the MRYR	1950~2006	Hydrological Method and Soil and Water Conservation Method	76.5~77.77	23.50	44.4~49.7	50.30
Sun et al. [51]	the Coarse Sand Area in the MRYR	1956~2010	Double Cumulative Curve Method	79.96	20.04	81.38	18.62
Gao et al. [44]	the MRYR	1975~2008	Double Cumulative Curve Method	70	30	80	20
Xu [52]	the Coarse Sand Area in the MRYR	1950~2007	Double Cumulative Curve Method			65	35
Yin [53]	the Coarse Sand Area in the MRYR	the 1950s ~1989	Precipitation, Runoff, and Sediment Load Statistical Models	59.70	40.30	45.50	54.50
Bao [54]	Hekou Town to LM Hydrological Station	1963~1986	Physical Model	50	50	58.20	41.80
Wang [55]	Hekou Town to LM Hydrological Station	1955~1989	Hydrological Method	66.70	33.30	37	63
Mu et al. [56]	Hekou Town to LM Hydrological Station	1952~1996	Hydrological Method and Soil and Water Conservation Method	38.40~60.51	24~61.60	7.3~66.99	21.84~92.70

5. Conclusions

The LM and TG hydrological stations in the MRYR, as well as hydrological stations along the tributaries of the middle reaches, such as Huangfu, Wenjiachuan, Baijiachuan, Ganguyi, Zhangjiashan, Zhuangtou, Huaxian, Hejin, Heishiguan, and Wuzhi, were selected. Based on the sequential analysis of the measured runoff and sediment load from 1950 to 2022, the following conclusions were drawn:

1. In the MRYR, the M–K test values for the LM and TG on the mainstream in the middle reaches were also less than −3.01, with both showing significant reductions in runoff depth. This suggests a gradual decline in the runoff generation capacity of the corresponding areas. Similarly, the M–K test value for the Yan River, a tributary, was −2.864, indicating a decreasing trend. The M–K test values for the other nine tributaries were all less than −3.01, showing significant decreasing trends. The

sediment transport modulus for both the mainstream and tributary hydrological stations in the MRYR had M–K test values less than −3.01, indicating a significant decreasing trend.

2. In the mainstream of the MRYR, the years with abrupt changes in runoff volume were 1985 and 1994, while the years with abrupt changes in sediment load were 1979 and 1996. Compared with those during the baseline period, the contributions of human activities to runoff during period I and period II were 69.99% and 94.69%, respectively. Similarly, compared with those in the baseline period, the contributions of human activities to sediment load during period I and period II were 88.52% and 98.49%, respectively.
3. In the MRYR tributaries, the contribution of human activities to the tributaries was significantly greater than that of precipitation. Compared to period I, the proportion of contributions from human activities increased significantly in period II, averaging 88.64%. The contribution of human activities to sediment load was high in both period I and period II. In period I, the average contribution was 82.54%, and in period II, it increased to an average of 98.66%.
4. In the MRYR, from the Toudaoguai to the TG hydrological stations, although there was a good positive correlation between runoff distribution and precipitation, the correlation between the sediment transport modulus and precipitation was not significant. From 1981 to 2022, the FVC generally showed an increasing trend. The peak periods for the construction of check dams were from 1970 to 1979 and from 2000 to 2009. The construction of reservoirs in the middle reaches began in 1956, with the most concentrated construction occurring from the 1970s to 1980s. The multiyear average water intake and consumption at the Toudaoguai-LM hydrological stations of the MRYR from 1998 to 2022 showed an upward trend, and there was an increasing trend in sediment transport in the last decade.

The annual runoff and sediment load in the MRYR show a decreasing trend. It is necessary to continue advocating for engineering measures to address soil erosion and to consolidate the existing achievements in management. These research findings contribute to understanding the patterns and mechanisms of runoff and sediment load changes in the Yellow River Basin, providing valuable reference for the management of runoff and sediment load in the Yellow River Basin. However, when analyzing the contributions of precipitation and human activities to the runoff and sediment load in the MRYR, only a general consideration was given to the contribution rates of human activities and precipitation. Human activities involve a combination of various soil and water conservation measures, as well as water conservancy projects, making it challenging to accurately quantify their impacts. Therefore, the quantitative relationships between these factors require further research.

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