

Dynamic changes of sediment load and water discharge in the Weihe River, China

Jianxia Chang¹ · Yunyun Li¹ · Jie Wei¹ · Yimin Wang¹ · Aijun Guo¹

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Abstract The abrupt reduction of the water discharge and sediment load in the Yellow River has attracted much attention during the past several decades. This paper investigates the temporal and spatial changes of annual sediment load and water discharge in the Weihe River basin, the largest tributary of the Yellow River, which contributes 40 % of the sediment and 26 % of the water to the Yellow River. The results suggest that sediment load and water discharge in the Weihe River basin from both mainstream and tributaries show significant decreasing trends (significance level of 0.05). The trends show the following three distinct stages: the fluctuating stage (1956–1969), the slowly decreasing stage (1970–1979) and the accelerated decreasing stage (1980–2010). Additionally, the water discharge decreases more quickly than sediment. Spatially, the greatest reduction in water discharge and sediment load occurs upstream of the river. Additionally, the decrease in water discharge and sediment load in the main stream is greater than in the tributary. The focal years of water discharge and sediment changes are the same for each station except for the Zhuangtuo Station, which were approximately 1970 and during the 1990s. Human activities contribute much more to changes in the hydrological series, and the percentage of human activity impacts on the water discharge are much larger than the sediment load for most of the periods. The relationship between the average monthly water discharge and the sediment load shows a clockwise loop curve. The change

points for the annual water discharge and the sediment load relationship occurred mainly in 1983 for most stations. The reduction in the water discharge and sediment load is caused mainly by human activities, especially soil and water conservation projects (such as afforestation, terraces, reservoirs and dams). In summary, the results in this study provide further evidence of the need for river basin management.

Keywords Yellow river · Water discharge · Sediment load · Human activity · Water discharge · Sediment load relationship

Introduction

In recent decades, the global changes resulting from climate change and human activities, including population increases, water use, changes in land use, and damming of rivers, have intensified at an increasing rate and have altered the global river systems. Rivers such as the Colorado, Mississippi, Indus, Nile, Yangtze and Yellow River have been reported to supply less sediment and water discharge to the sea due to water abstraction and changes in land use (e.g., afforestation and deforestation) (Wang et al. 2015a, b; Zheng et al. 2015; Gao et al. 2011; Syvitski et al. 2005; Panda et al. 2011; Meade and Moody 2010). Milliman (2001) investigated the sediment flux of major rivers in Europe and found that the sediment flux of many rivers has decreased significantly over the past 50 years. Walling and Fang (2003) studied the long-term runoff in the sediment sequence data of 145 rivers in Asia, Europe and North America. The results showed that approximately 50 % of the river sediment flux changes in the global context of climate change included a decrease in the majority of the

✉ Jianxia Chang
chxiang@xaut.edu.cn

¹ State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an 710048, China

sediment flux, and approximately 50 % of the river sediment flux was essentially unchanged. Among these rivers, the Yellow River provides an excellent illustration of the interaction between a decrease in precipitation, extensive implementation of soil and water conservation, and sediment control measures (Miao et al. 2011; Fu et al. 2007; Yao and Xu 2013). Water and sediment discharges of the Yellow River have been reported to have decreased to less than 20 % of their levels in 1950s–1960s (Xu 2003; Yao and Xu 2013). Conversely, some rivers have shown significant increases in water discharge due to an increase in precipitation or thawing of glaciers and permafrost due to climate warming (Walling and Fang 2003) or have shown significant increases in sediment discharge due to deforestation and mining activity (Walling 2006).

The causes of changes in water discharge and sediment load differ from river to river and vary with time. Understanding the variation in river sediment load and water discharge as well as river dynamic conditions is essential for the prediction of the future evolution of rivers and drainage basin management. Therefore, there is a need to investigate the variation in specific rivers to aid regional environmental management. Furthermore, quantitative assessments of climate and human impacts on long-term hydrological response are an important topic in hydrology and have elicited many qualitative studies (Vörösmarty et al. 2003; Wang et al. 2015a, b; Liqueste et al. 2009; Ahn and Merwade 2014).

The Yellow River is the second largest river in China and is known worldwide for its exceedingly high sediment concentration. Yellow River runoff is one-twentieth of the runoff of the Yangtze River, but its sediment load is three times that of the Yangtze. The average annual sediment load deposited into the sea from the Yellow River was 12×10^8 t during 1919 and 1960 and 6.53×10^8 t from 1960 to 2000. However, the amount decreased to 1.51×10^8 t from 2000 to 2005 (Miao et al. 2010; Wang et al. 2012; Lu 2004; Lu and Siew 2006). The Weihe River, located in the middle reaches of the Yellow River basin, is the largest tributary of the Yellow River, and 35–40 % of the Yellow River sediment is from the Weihe River. However, since 1950, the sediment load to the Yellow River delivered by the Weihe River began to decrease due to the combined effects of climate change and human activities. The average sediment load to the Yellow River was, respectively, 16×10^8 , 6.53×10^8 and 1.51×10^8 t/year from 1919 to 1960, 1961 to 2000, and 2001 to 2005. Studies by Liu et al. (2008) showed that the annual sediment yield in the middle reaches of the Yellow River is extremely higher than the sediment yield in the upper and lower reaches. In the middle and lower reaches, the sediment yield is dramatically influenced by human activities (such as reservoirs and soil and water conservation

programs). Gao et al. (2011) found that the human intervention (e.g., soil and water conservation measures) and climate changes (e.g., temperature and precipitation) were responsible for the dramatically decreasing streamflow and sediment load in the middle reaches of the Yellow River.

Since the early 2000s, many research papers in international and Chinese journals have reported an ongoing decrease in the sediment load and water discharge of the Yellow River and have examined relevant issues, including attempts to answer the following questions: When did the decreasing trend begin? What are the main causes of this trend? In which areas has the sediment decline mainly occurred? Most of the research papers focus primarily on the main stream (Zhao et al. 2014; Yue et al. 2014). Wang et al. (2007) analyzed sediment load variations along the Yellow River basin and found that the gradual sediment decrease could be ascribed to reservoirs and dam construction in the upper reaches, soil and water conservation practices caused the decrease in sediment load in the middle reaches, and river sediment reduction could be attributed to water abstraction in the lower reaches. Mu et al. (2012) analyzed the recent 90 years of sediment discharge changes and influencing factors in the Yellow River based on the hydrological station annual sediment discharge series at the Shaanxian County Station and concluded that the sediment reduction caused by human activities and rainfall is 81 and 19 %, respectively. However, very few studies have focused on sediment load variability in the Weihe River. In addition, these studies have mostly concentrated on periods between the start of the 1960s to the end of the 1990s. A huge project, “Grain for Green” (GFG), costing more than 30 billion US dollars, was launched by the Chinese government at the end of 1999 and was implemented countrywide until 2002 (Miao et al. 2010). The objective of this program was to increase vegetation coverage on steep hillsides by planting trees or sowing grass on former cropland. In the Weihe River basin, since the 1990s, soil preservation measures have been increasingly employed, and more projects have been conducted to reduce soil erosion in the drainage basin. A better understanding of the temporal changes in sediment and water discharge is very useful for soil and water conservation, eco-rehabilitation and river basin management in the Weihe River basin.

The goal of our study is to make a systematic, quantitative analysis of the water discharge and sediment load responses to changes in human activities and climate in the Weihe River basin. The specific objectives of this study are (1) to statistically analyze both spatial and temporal variation of sediment load and water discharge recorded in the main stream and tributaries, (2) to detect the relationship between sediment load and water discharge, and (3) to assess the contributions of climate change and basin-wide

human activities to the decreases in sediment load and water discharge and to elucidate the causes of such dramatic decreases. This research will help to characterize the variation of runoff and sediment load of the Weihe River and provide a stronger base for decision-making in the area of environmental management.

Study area

The study area, the Weihe River basin (WRB) with a drainage area of 134,800 km², is located between 33–37°N and 104–110°E in northwest China. The location of the study area is shown in Fig. 1. The Weihe River, the largest tributary of the Yellow River of China, originates from mountains in Gansu Province and runs for 818 km from west to east before entering the Yellow River. The elevation in the catchment decreases from west to east: The lowest elevation is 325 m at Tongguan Hydrologic Station, and the highest elevation is 3767 m at Mount Taibai. North of the WRB is the Loess Plateau, and south of the WRB are the Qinling Mountains. Upstream of the WRB are mainly the Loess Hills, covering an area of more than 70 % in this region. North, central, and south of the middle and lower reaches of the WRB is the Loess Plateau, an alluvial plain and rocky area in the Qinling Mountains. The two large tributaries in the north of the WRB are the Jinghe River and the Luohe River. WRB is one of the most serious soil erosion areas in the Yellow River Basin. The extensive area of the soil erosion has covered an area of 103,600 km² (44,700 km² of the main stream, 39,500 km² of the Jinghe River, and 19,400 km² of the Luohe River), approximately 76.9 % of the catchment area in the WRB.

The WRB is located in a transitional zone of drought areas and wet areas, and the climate is dry and chilly in

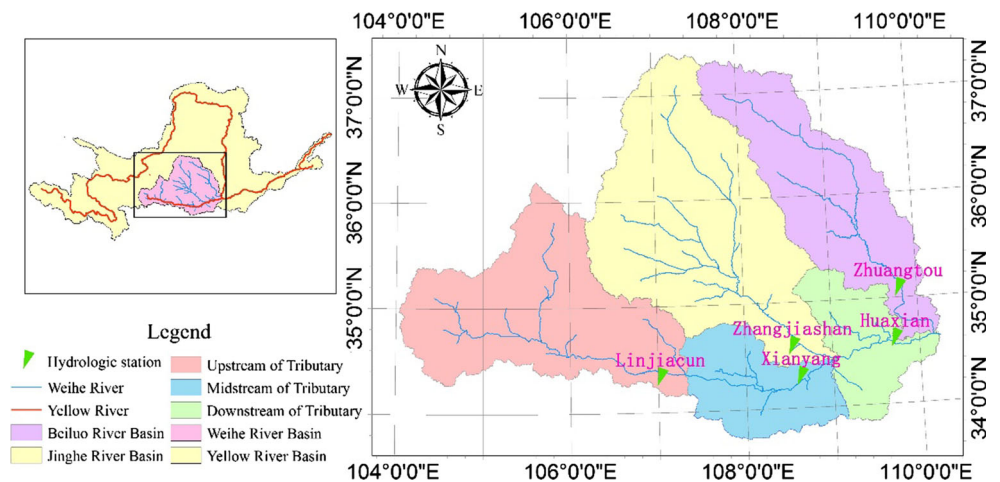
the winter and hot and rainy in the summer. The annual average temperature in the catchment is 7.8–13.5 °C, and the maximum and the minimum values for average monthly temperature are 42.8 °C in July and –28.1 °C in January. The annual average precipitation is over 600 mm with a distinct spatial pattern. The highest precipitation occurs in the southeast part of the catchment, while the northwest parts receive less precipitation. The precipitation in the period from July to October (the flood season) accounts for 63.2 % of the annual precipitation. The annual water discharge and sediment load of the Weihe River to the Yellow River (averaged for the period of 1956–2010) are $74.5 \times 10^8 \text{ m}^3$ and $3.88 \times 10^8 \text{ t}$, respectively.

Data series and methods

Data series

In this study, the daily precipitation, water discharge and sediment load during the period of 1956–2010 in the WRB were explored to represent the hydrological responses to climate variation and human activities in the catchment. Daily measurements of precipitation at 21 meteorological stations were collected from the China Meteorological Administration (CMA). The water discharge and sediment load at five hydrological stations were all provided by the hydrological bureau of the Yellow River Conservancy Commission, whose main responsibility is monitoring, collecting and distributing this information regarding the Yellow River. The measurement criteria of the data for different years were common and consistent through the entire recorded period, and the data quality for the runoff and sediment was strictly controlled before the data were released.

Fig. 1 Location maps of a the Yellow River basin; b the entire Weihe River Basin



Methodology

Due to the distribution of the water discharge, the sediment load and the precipitation time series were abnormal, and the widely applied distribution-free nonparametric test, the Mann–Kendall (MK) test, was used to analyze the changes in the above hydrological data series in the WRB.

To address the impacts of human activity on sediment load and water discharge, double-mass curves (DMCs) and linear regression lines were plotted to show the correlation between cumulative annual sediment load and precipitation. A double-mass curve is a plot of the cumulative values of one variable against the cumulative values of another related variable for a concurrent period of time. In general, the DMC is expected to be a straight line if two variables are proportional, and the slope of this line will represent the constant of proportionality between the two variables. However, in most cases, a break in the slope can be identified in the DMCs, suggesting the point in the time series at which a change occurred in the constant of proportionality. Double-mass curves can be applied to check the consistency of a hydrological record (e.g., precipitation, water discharge and sediment load) and the relationships between two hydrological records (e.g., precipitation–discharge, precipitation–sediment, and discharge–sediment). Recently, the double-mass curve method has become a useful tool for identifying the changes in the river responses due to anthropogenic disturbances (Walling 2006). In this study, the double-mass curve method was employed to discern the breaking points when human activities imposed important influences on the river discharge and sediment load.

Results and discussions

Temporal and spatial distribution of water discharge and sediment load

The Weihe River has a relatively low water discharge but a high sediment load compared to the other rivers in the world. According to records at Huaxian and Zhuangtuo Hydrological Stations, the sediment load delivered by the Weihe River into the Yellow River was 3.88×10^8 t/year from 1956 to 2010, approximately 39.87 % of that into the Yellow River, whereas the water discharge was 74.50×10^8 m³/year, only 26.03 % of that into the Yellow River.

The WRB can be divided into three areas according to a combination of physical and geographical elements. The basin above Linjiacun is part of the Loess Plateau, mostly located in the Qinghai–Tibet Plateau (Fig. 1). This area was an important source of the sediment load with an

annual average value of 1.04×10^8 t, accounting for 26.80 % of the whole sediment load. The annual average water discharge was 19.93×10^8 m³/year, accounting for 26.75 % of the whole basin value. Therefore, the upper reaches of the WRB constitute a section with relatively balanced amounts of water discharge and sediment load. Water discharge in the middle reaches from Linjiacun to Xianyang Station was 19.15×10^8 m³/year, accounting for 25.70 % of the whole basin value, and the sediment yield was zero for this section. At Xianyang Station, the sediment load was 1.02×10^8 t/year, which only accounts for 26.29 % of the basin-wide load, increasing to 3.11×10^8 t/year (80.15 % of the basin load) at Huaxian Station (Table 1). Therefore, the lower reaches were characterized by a high sediment load. Table 1 shows that nearly 74 % of the sediment was generated from the lower reaches, where the dominant geological feature was the wind-deposited Loess Plateau, composed mainly of loosely compacted silt, which is very prone to erosion. In the lower reaches of the WRB, the Jinghe River area was 4.18×10^4 km², and the water discharge as merely 18.34 % of the total basin record, while the sediment load accounts for 56.70 %, which could have resulted in the sediment deposition in the lower reaches of the WRB. The extreme high specific sediment load of this tributary suggests that these areas are the regions with the most severe soil erosion.

Figure 2 shows the distribution characteristics of the water discharge and sediment load through the 12 months at Linjiacun, Xianyang, Huaxian, Zhangjiashan and Zhuangtuo Stations. The distribution regularity of water discharge was broadly similar at different stations. The water discharge was concentrated mainly in July to October, which accounts for more than 50 % of the annual water discharge at all the hydrological stations (range from 54 to 65 %). The sediment load also has a variation similar to water discharge in the flood season of the river. The sediment load was concentrated in June to September, when the sediment load accounted for 88–98 % of the annual value. Particularly, in July and August, the sediment load accounted for 61.92–83.15 % of the annual sediment load. The sediment load was more concentrated than the water discharge during the flood season.

Change analysis of water discharge and sediment

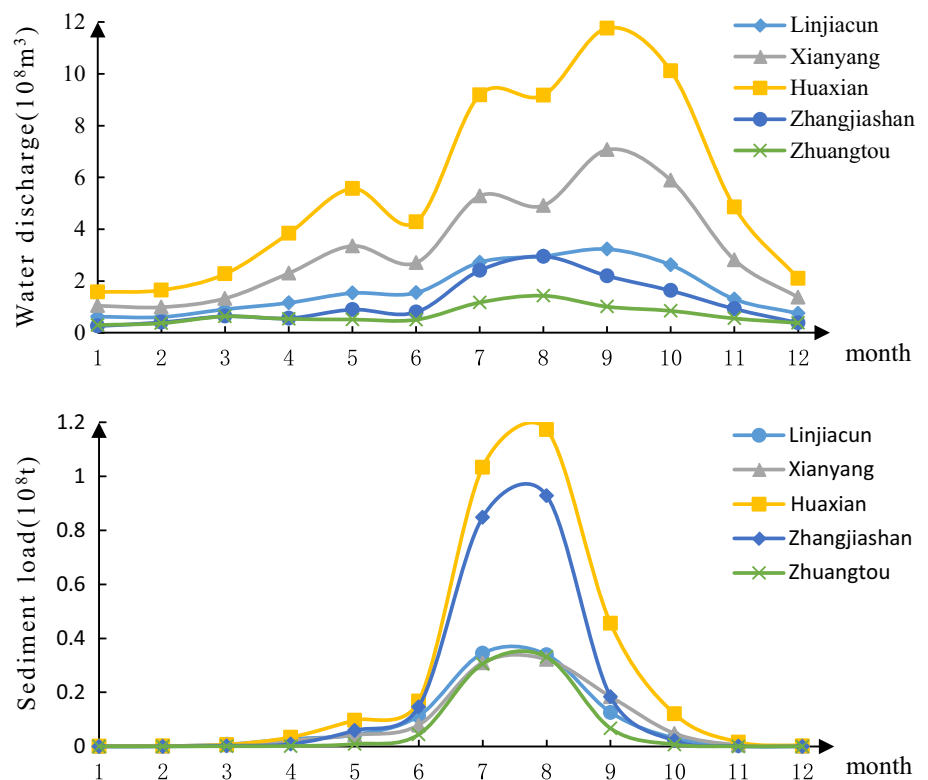
Decadal variations

Table 2 lists the decadal average annual water discharge and sediment loads and also presents the percentage difference with respect to the baseline value (1956–1970). Except for the Zhuangtuo Station, the water discharge and sediment load series during the period of the 1970s–2000s had lower values than the water discharge and sediment

Table 1 Information about hydrological stations in Weihe River basin

Station	Latitude (N)	Longitude (E)	Elevation (m)	Area		Average annual water discharge		Average annual sediment load	
				km ²	%	10 ⁸ m ³	%	10 ⁸ t	%
Linjiacun	34.21	107.00	615	32,850	25.08	19.93	26.75	1.04	26.80
Xianyang	34.17	108.42	390	49,822	38.03	39.08	52.46	1.02	26.29
Huaxian	34.44	109.42	342	105,350	80.42	66.34	89.05	3.11	80.15
Zhangjiashan	34.35	108.35	342	41,800	31.91	13.66	18.34	2.20	56.70
Zhuangtou	35.02	109.50	1082	25,645	19.58	8.16	10.95	0.77	19.85
Upper reaches	Above Linjiacun			32,850	25.08	19.93	26.75	1.04	26.80
Middle reaches	Linjiacun–Xianyang			16,972	12.96	19.15	25.70		
Lower reaches	Down Xianyang			81,173	61.97	35.42	47.54	2.86	73.72

Fig. 2 Distribution characteristics of monthly water discharge and sediment load of the WRB



load series during the baseline period, with the levels of reduction growing larger with time for most of the stations. Their changes were divided into the following three stages: the fluctuating stage (1956–1969), the slowly decreasing stage (1970–1979) and the accelerated decreasing stage (1980–2010). The most significant decrease in the water discharge series occurred in the 1990s at Huaxian Station located downstream of the river, where the reduction in the water discharge was $48.49 \times 10^8 \text{ m}^3/\text{year}$. However, the greatest percentage changes occurred in the 2000s at Linjiacun, upstream of the river, with 63.02 %. For the

observed sediment load series, the greatest change occurred in the 2000s at Huaxian, where the reduction was $3.50 \times 10^8 \text{ t/year}$, whereas the greatest percentage change occurred also in the 2000s at Linjiacun, with an 86.34 % reduction.

Decreasing trend analysis

Table 3 and Fig. 3 show the trends analysis by the Mann–Kendall test and a linear regression for the sediment load and water discharge at five hydrological stations in the

Table 2 Statistical characteristics of annual sediment distribution in Weihe Basin

Station	Year	Sediment load (10^8 t)	%	Nonuniform coefficient C_v	Water discharge (10^8 m ³)	%	Nonuniform coefficient C_v
Linjiacun	1956–1969	1.83		0.40	26.96		0.37
	1970–1979	1.42	–22.40	0.78	22.23	–17.54	0.51
	1980–1989	0.96	–47.54	0.39	23.22	–13.87	0.44
	1990–1999	0.52	–71.58	0.85	12.9	–52.15	0.88
	2000–2010	0.25	–86.34	0.63	9.97	–63.02	0.56
	Average	1.04	–43.17	0.84	19.93	–26.08	0.69
Xianyang	1960–1969	1.91		0.40	58.82		0.34
	1970–1979	1.37	–28.27	0.88	36.76	–37.50	0.50
	1980–1989	0.84	–56.02	0.40	45.46	–22.71	0.39
	1990–1999	0.46	–75.92	0.79	22.49	–61.76	0.64
	2000–2010	0.28	–85.34	0.97	23.48	–60.08	0.57
	Average	1.02	–46.60	0.89	39.08	–33.56	0.57
Huaxian	1956–1969	4.85		0.61	92.28		0.37
	1970–1979	3.74	–22.89	0.68	59.48	–35.54	0.45
	1980–1989	2.69	–44.54	0.50	79.16	–14.22	0.40
	1990–1999	2.76	–43.09	0.42	43.79	–52.55	0.45
	2000–2010	1.35	–72.16	0.54	46.42	–49.70	0.43
	Average	3.11	–35.88	0.71	66.34	–28.11	0.51
Zhang jiashan	1956–1969	3.105		0.71	18.455		0.46
	1970–1979	2.49	–19.81	0.61	12.74	–30.97	0.50
	1980–1989	1.64	–47.18	0.61	13.68	–25.87	0.43
	1990–1999	2.43	–21.74	0.47	13.78	–25.33	0.24
	2000–2010	1.14	–63.29	0.43	10.36	–43.86	0.43
	Average	2.2	–29.15	0.70	13.66	–25.98	0.48
Zhuang tou	1956–1969	1.19		0.63	9.12		0.38
	1970–1979	0.91	–23.53	0.44	9.21	0.99	0.29
	1980–1989	0.46	–61.34	0.81	8.35	–8.44	0.32
	1990–1999	0.97	–18.49	0.75	7.5	–17.76	0.25
	2000–2010	0.25	–78.99	0.97	6.22	–31.80	0.36
	Average	0.77	–35.29	0.82	8.16	–10.53	0.36

Table 3 Results of the Mann–Kendall test and linear regression of runoff

Station	Water discharge		Sediment load	
	Mann–Kendall Z statistic	Linear regression slope	Mann–Kendall Z statistic	Linear regression slope
Linjiacun	–5.26	–0.49	–6.27	–0.04
Xianyang	–4.30	–0.84	–6.13	–0.04
Huaxian	–3.55	–1.08	–4.35	–0.07
Zhangjiashan	–4.26	–0.17	–2.68	–0.03
Zhuangtou	–3.47	–0.07	–3.87	–0.02

mainstream and tributaries in the WRB from the years 1956 to 2010. The maximum annual water discharge in the whole basin occurred in 1964 (207.65×10^8 m³), and the minimum occurred in 1997 (21.79×10^8 m³). The maximum annual sediment load occurred in 1964 (12.71×10^8

t), and the minimum occurred in 2008 (0.58×10^8 t). The trends analysis indicates that the average annual sediment load and annual water discharge at all the hydrological stations exhibited significant downward trends at the $\alpha = 0.05$ significance level. According to the data from

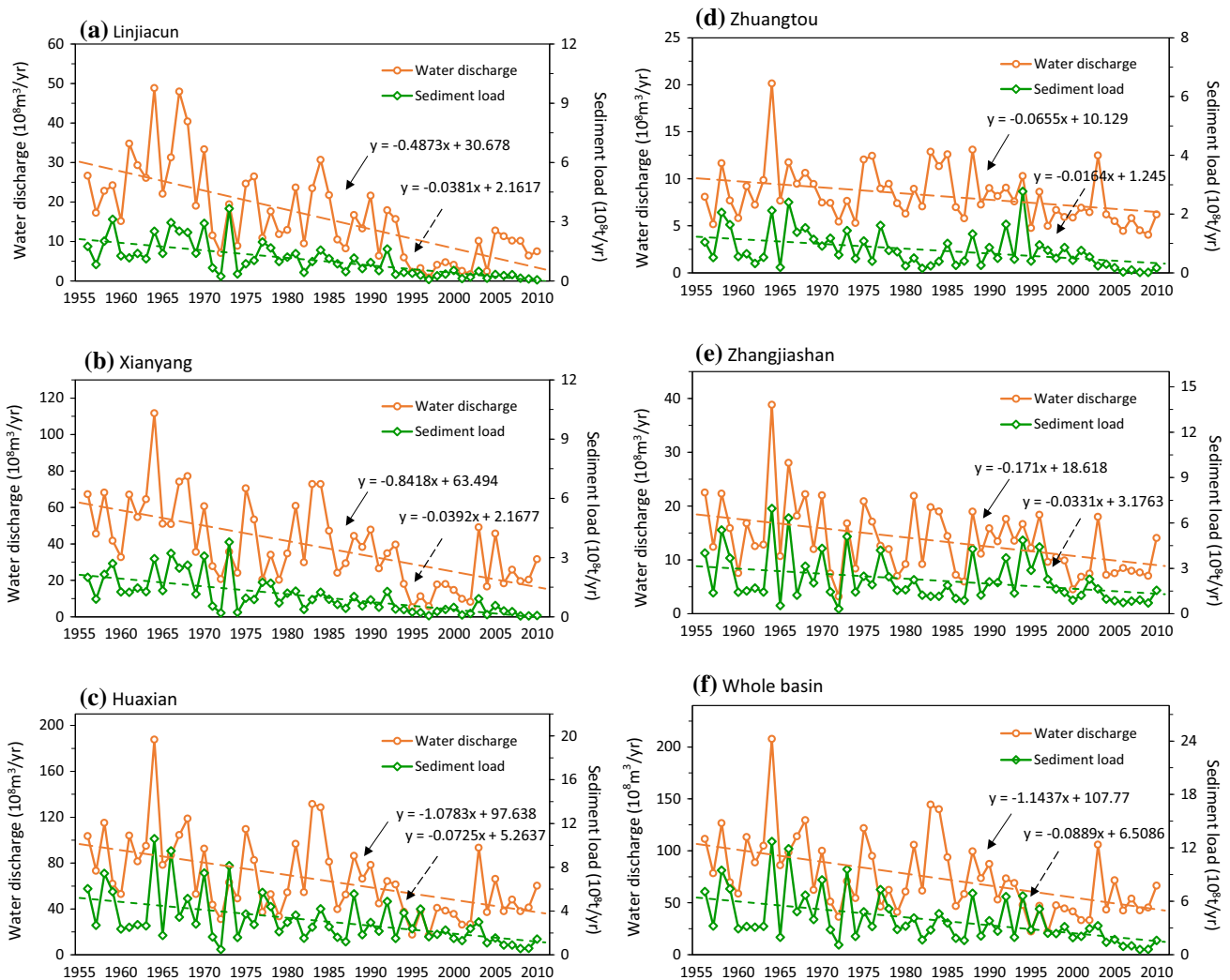


Fig. 3 Annual water discharge and annual sediment load from 1956 to 2010 and linear trends

1956 to 2010, the long-term average annual sediment load was 3.93×10^8 t, and the annual runoff volume was 74.60×10^8 m³. For the annual runoff, $C_v = 0.48$, whereas for the long-term annual sediment load, $C_v = 0.70$, indicating that the sediment was more unstable than the runoff.

Figure 3 also shows that, generally, a large sediment load occurred in wet years, and a small sediment load occurred in dry years, controlled by the flow sediment transport capacity. There are a few exceptions, e.g., 1996, 2005, and 2006, for which sediment loads are relatively lower compared to other years with similar runoff volumes, indicating that the time of high flow within a year also plays an important role in the annual sediment load of the river basin. With a linear slope of -1.08 , the annual water discharge of the WRB fell more quickly, especially after the 1990s, while the annual sediment load showed a weak

falling trend, with a linear slope of -0.08 . Furthermore, both of the falling tendencies were significant.

Table 3 shows that, among the 3 stations along the mainstream, the water discharge and sediment load decreasing rate during 1956–2010 period varied from -1.08×10^8 to -0.49×10^8 m³/year and -0.07×10^8 to -0.04×10^8 t/year, respectively. The most significant downward trends were detected at Linjiacun Station (Z values of -5.26 and -6.27 for water discharge and sediment load, respectively), with the decreasing rate of -0.49×10^8 m³/year and -0.04×10^8 t/year, respectively. The lowest decreasing rate of -1.08×10^8 m³/year and -0.07×10^8 t/year was found at Huaxian Station (Z values of -3.55 and -4.35), respectively. The main reason for the downward trends in the sediment load in the WRB was because of the implementation of soil and water conservation measures (Mu et al. 2007; Zhao et al. 2014).

The water discharge and sediment load at all of the tributary gauging stations suggested significant decreasing trends at the 95 % confidence level. The statistical Z values ranged from -4.26 to -2.68 , which were detected at the Zhangjiashan Station on the Jing River and the Zhuangtuo Station on the Beiluo River. The corresponding decreasing rates for water discharge and sediment load at Zhangjiashan Station were $-0.17 \times 10^8 \text{ m}^3/\text{year}$ and $-0.03 \times 10^8 \text{ t/year}$, and at the Zhuangtuo Station, they were $-0.07 \times 10^8 \text{ m}^3/\text{year}$ and $-0.02 \times 10^8 \text{ t/year}$, respectively. The decrease in the water discharge and sediment load on the main stream was greater than the decrease on the tributary.

Relative contributions of climate variability and human activity effects for sediment load and water discharge

Human impacts discerned from double-mass curves

The impact of climatic change on the sediment load and water discharge of the rivers was embodied mainly in the variability of the precipitation (Xu 2003). Wang et al. (2006, 2007) suggested that the lower precipitation in the Yellow River basin has resulted in a 30 % decrease in the sediment load over the past 56 years. To assess the impacts of human activities on sediment load and water discharge in the WRB, the cumulative annual sediment load and cumulative annual precipitation as well as the cumulative annual water discharge and cumulative annual precipitation were plotted into a double-mass curve (Figs. 4, 5). If there was no evidence of the impact of human activities on hydrological processes, the double-mass curve was expected to be a straight line, representing the best-fitted relationship between sediment load and water discharge with precipitation. However, there were some breaks found in the double-mass curves in both plots, which indicated that the variations in hydrological processes were affected by both precipitation and human activities in the catchment.

Taking Linjiacun as an example, the double-mass curve between annual precipitation and sediment load clearly reflects the impact of human activities on sediment load. In the double-mass curve of the annual sediment load and annual precipitation, two break points occurring in 1970 and 1992 were observed. Based on the breaks identified in the double-mass curves, the linear regression equations were established for different periods. The best-fitted linear regression equations between the annual sediment load and the annual precipitation for the three periods divided by the turning points in the double-mass curve are shown in Fig. 4a. The best-fitted lines of the relationship for the periods after 1970 were all found to be located below the

Fig. 4 Double-mass curve of accumulated annual precipitation and accumulated sediment load

line for the period 1956–1970, which indicates the sediment load decreased after the year 1970.

The equations for the benchmark period (1956–1970) were used to represent the effect of precipitation variation on the sediment load. Using the data measured before 1970 (the benchmark period), a regression relationship between precipitation and sediment load was established (Line y_0). Then, the regression line was extended to the analyzed period (1971–2010), which denotes the sediment transport under the same precipitation conditions and human impact as in the benchmark period. Assuming that there is no human intervention, the variation would have responded solely to the precipitation change. The calculated polyline in Fig. 4b was generated by inputting the measured precipitation in the analyzed period into the established regression relationship, which indicates the sediment transport under actual precipitation conditions but still with weak human intervention as in the benchmark period. The calculated annual sediment load was obviously greater than the measured series after 1970, and the difference became greater after 1992, although both had a decreasing trend. Furthermore, the measured sediment loads were indicative of the actual changes in sediment loads as influenced by both human impact and precipitation. Thus, the difference between the calculated and measured series demonstrated the influence of human activities. By taking the percentage, the contribution rates of human impact and precipitation were then discerned.

Effects of climate variability and human activities on water discharge and sediment load

In the WRB, two different turning years were detected for water discharge and sediment load variations at all hydrological stations, indicating that water discharge and sediment changes in the whole river basin were characterized by three different phases, one benchmark period and two analyzed periods. The identification of multiple turning years suggests that the observed sediment changes were the combined results of natural and enhanced anthropogenic factors over the past decades. The turning years for water discharge and sediment changes were the same for each station except the Zhuangtuo Station. Additionally, the first turning year was 1970 for different stations. The differences in the turning year indicate different beginnings of crucial anthropogenic influences on the water discharge and sediment changes in the basin, particularly between the tributaries and the lower reaches.

The contributions of climatic variation and human activities to the water discharge and sediment load are

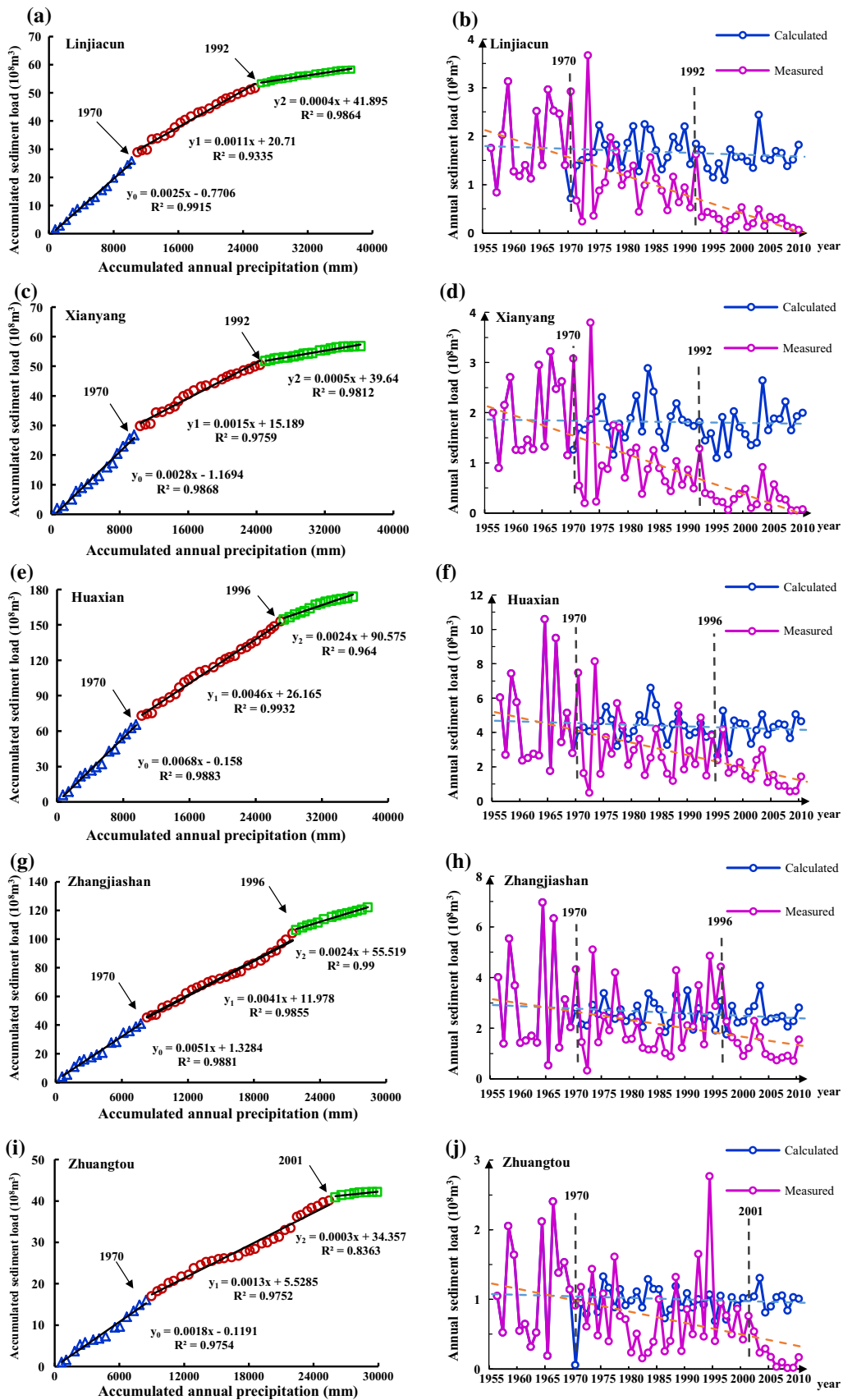


Fig. 5 Double-mass curve of accumulated annual precipitation and accumulated water discharge

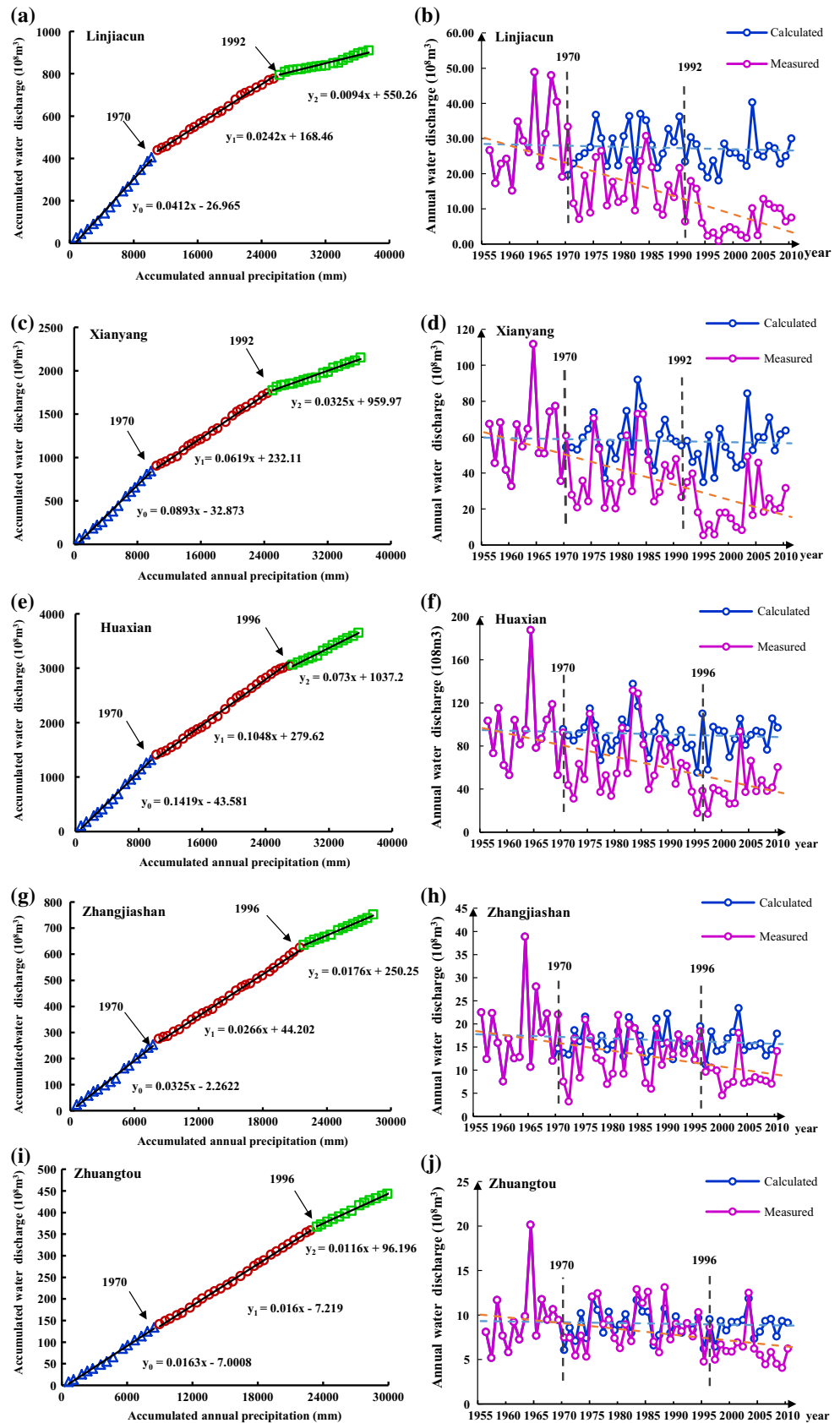


Table 4 Influence of climate change and human activities on sediment load of Weihe River

Station	Periods	Measured	Calculated	Total reduction	Precipitation		Human activities	
					Reduction volume	Contribution rate (%)	Reduction volume	Contribution rate (%)
Linjiacun	1956–1970	1.83						
	1971–1992	1.19	1.69	0.64	0.14	21.88	0.50	78.13
	1993–2010	0.39	1.59	1.44	0.24	16.67	1.20	83.33
Xianyang	1956–1970	1.91						
	1971–1992	1.11	1.78	0.8	0.13	16.25	0.67	83.75
	1993–2010	0.37	1.73	1.54	0.18	11.69	1.36	88.31
Huaxian	1956–1970	4.85						
	1971–1996	3.06	4.34	1.79	0.51	28.49	1.28	71.51
	1997–2010	1.35	4.32	3.50	0.53	15.14	2.97	84.86
Zhangjiashan	1956–1970	3.11						
	1971–1996	2.19	2.74	0.92	0.37	40.22	0.55	59.78
	1997–2010	1.14	2.55	1.97	0.56	28.43	1.41	71.57
Zhuang tou	1956–1970	1.19						
	1971–2001	0.78	1.09	0.41	0.10	24.39	0.31	75.61
	2002–2010	0.25	1.00	0.94	0.19	20.21	0.75	79.79

Table 5 Influence of climate change and human activities on water discharge of Weihe River

Station	Periods	Measured	Calculated	Total reduction	Precipitation		Human activities	
					Reduction volume	Contribution rate (%)	Reduction volume	Contribution rate (%)
Linjiacun	1956–1970	28.99						
	1971–1992	16.83	28.09	12.15	0.90	7.40	11.25	92.60
	1993–2010	7.05	25.84	21.94	3.15	14.34	18.79	85.66
Xianyang	1956–1970	60.16						
	1971–1992	40.75	59.39	19.41	0.78	4.00	18.64	96.00
	1993–2010	21.62	55.21	38.55	4.95	12.85	33.59	87.15
Huaxian	1956–1970	93.95						
	1971–1996	64.01	90.95	29.95	3.01	10.05	26.94	89.95
	1997–2010	43.33	88.64	50.62	5.31	10.50	45.31	89.50
Zhangjiashan	1956–1970	18.05						
	1971–1996	13.77	16.43	4.27	1.61	37.75	2.66	62.25
	1997–2010	9.05	15.89	9.00	2.16	24.01	6.84	75.99
Zhuang tou	1956–1970	9.55						
	1971–1996	8.63	8.94	0.92	0.61	66.93	0.30	33.07
	1997–2010	6.14	8.85	3.41	0.70	20.46	2.71	79.54

summarized in Tables 4 and 5 for the periods analyzed. The data listed are the annual arithmetic average values, where the sign reflects the direction of the dominant impacts. The water discharge and sediment load showed consistently decreasing changes over the whole period after the benchmark period. In general, human activities evidently contributed much more to changes in the hydrological series. The percentage impacts of human activities were much larger on the water discharge than the sediment

load for most of the periods. For the sediment load reduction after 1970, the impact of human activities showed a general rising trend. In the first phase, the contribution rate of the human activities ranged from 59.78 to 83.75 %, while the contribution rate of the human activities ranged from 71.57 to 88.31 % in the second phase. The most significant impact on the water discharge change was a reduction of approximately $50.62 \times 10^8 \text{ m}^3$, which occurred after 1996 at the Huaxian Station and was due to

human activity. Additionally, the hydrological stations located in the main stream were greatly influenced by human activities, and the contribution ratios were more than 85.66 %. In particular, the Xianyang Station, during 1971–1992, reached 96.00 %.

Relationship between sediment load and runoff volume (RSR)

The average monthly variation of RSR is drawn in Fig. 6, in which numbers 1–12 represent the months. The relationship between average monthly water discharge and sediment load can be observed to exhibit a clockwise loop curve. The monthly sediment loads increased during January to August and decreased after that period. Because the flood season of the WRB began in July and the dramatic increase in precipitation led to intense surface erosion, the sediment load reached a maximum in July and August. The relatively scarce precipitation produced less water discharge and sediment load in spring and winter. With the equal values for water discharge, the sediment load from January to August was greater than the sediment load occurring from September to December. At the Xianyang Station, the loop curve shows a counterclockwise change in July and August, indicating that the water discharge in July was greater than in

August, while the sediment load showed the opposite relationship. The main reason for this change is that the precipitation intensity in August was greater than in July in the control area of Xianyang Station, so the erosion intensity was stronger, resulting in the differences in sediment loads.

To analyze the change in RSR for the WRB, the double-mass curves of the annual water discharge and the sediment load at hydrological stations are plotted in Fig. 7. The change points of the annual RSR occurred mainly at approximately 1983 at the 5 stations except Linjiacun Station, where they occurred in 1975. The best-fitted linear relationships between the cumulative runoff and sediment are also shown in Fig. 7. High correlation coefficients were found for all of the relationships, and the correlation coefficients for the years before the change point were higher than after the change point. Additionally, the deflection of the double-mass curve increases gradually from upstream to downstream, illustrating that the change in RSR grows gradually.

Potential influence factors for the sediment load change

The Weihe River is a major source of drinking water, industrial water, and irrigation in the central plain, which

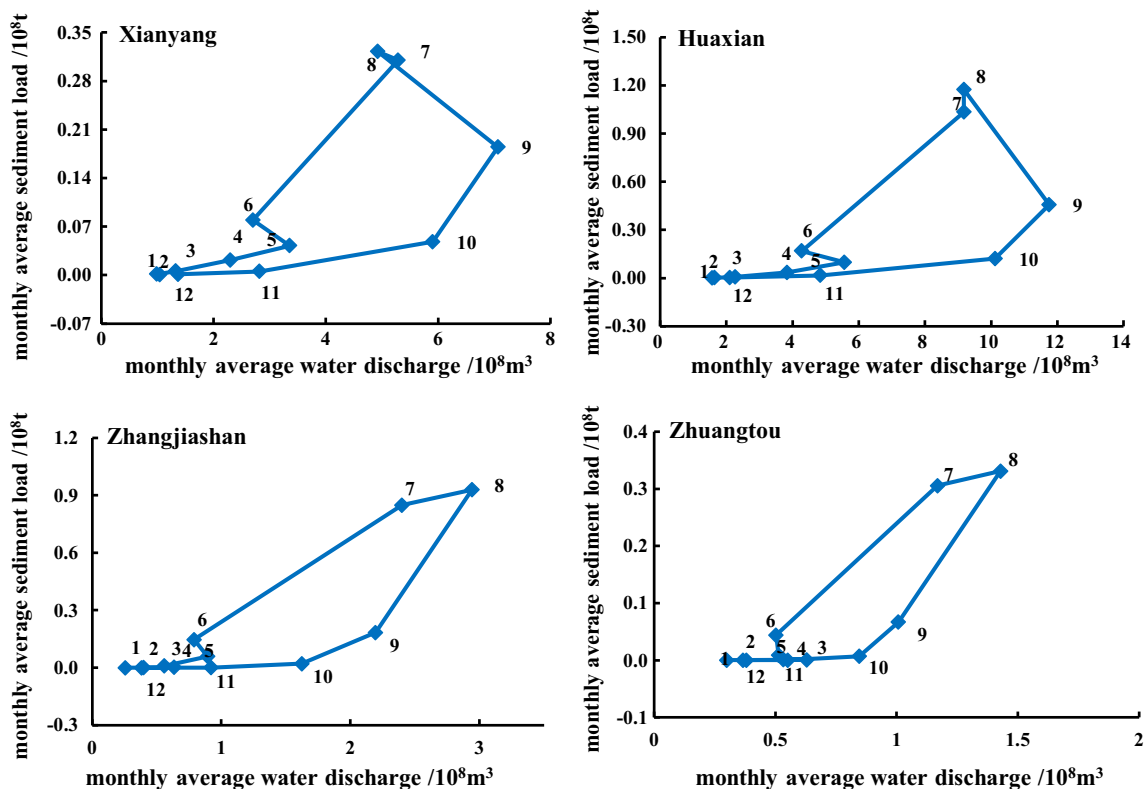
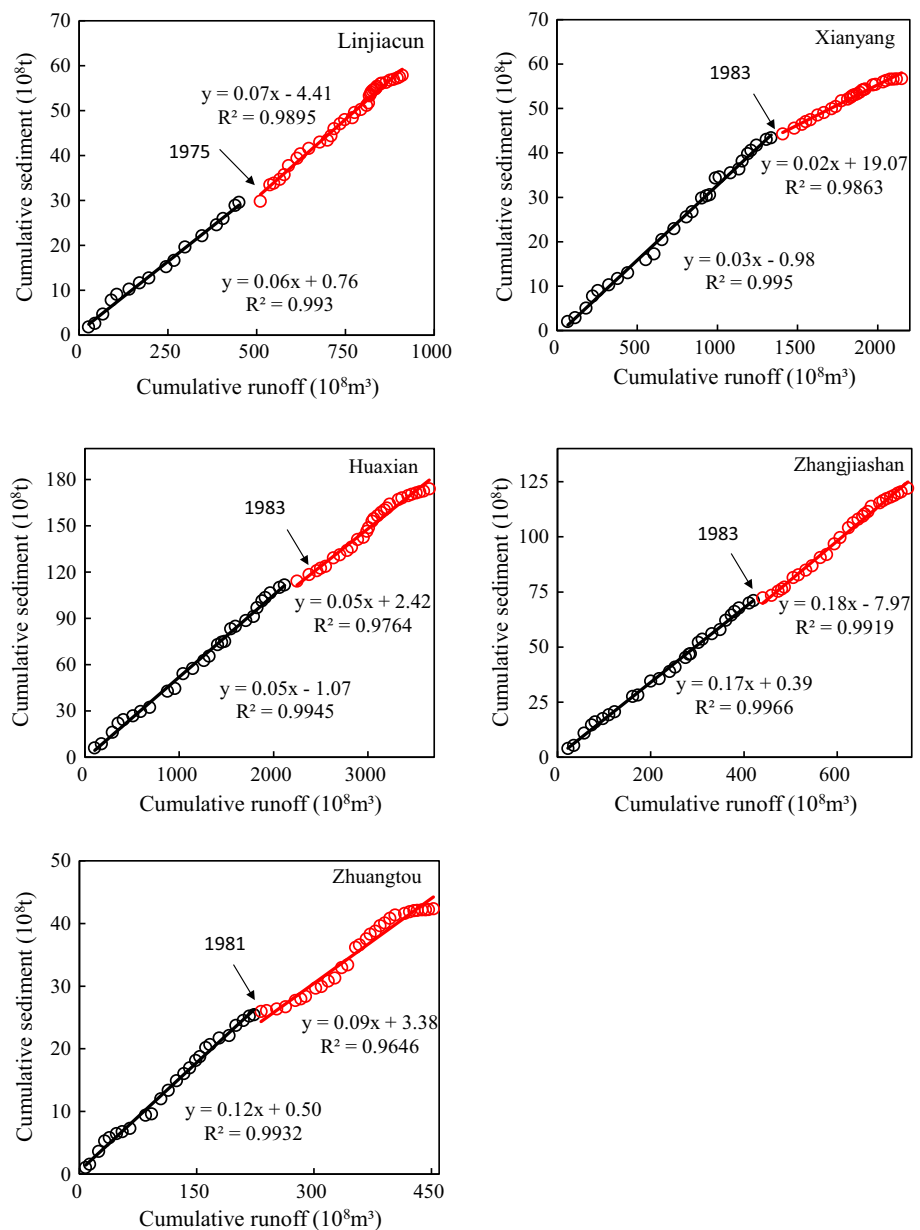


Fig. 6 Correlation curve of average monthly water discharge and sediment load in the WRB

Fig. 7 Double-mass curves of runoff and sediment for hydrological stations in the WRB



hosts 76 major cities with a total population of 22 million. The Weihe River valley is also the main grain-yielding area and an important industrial and commerce area in northwestern China.

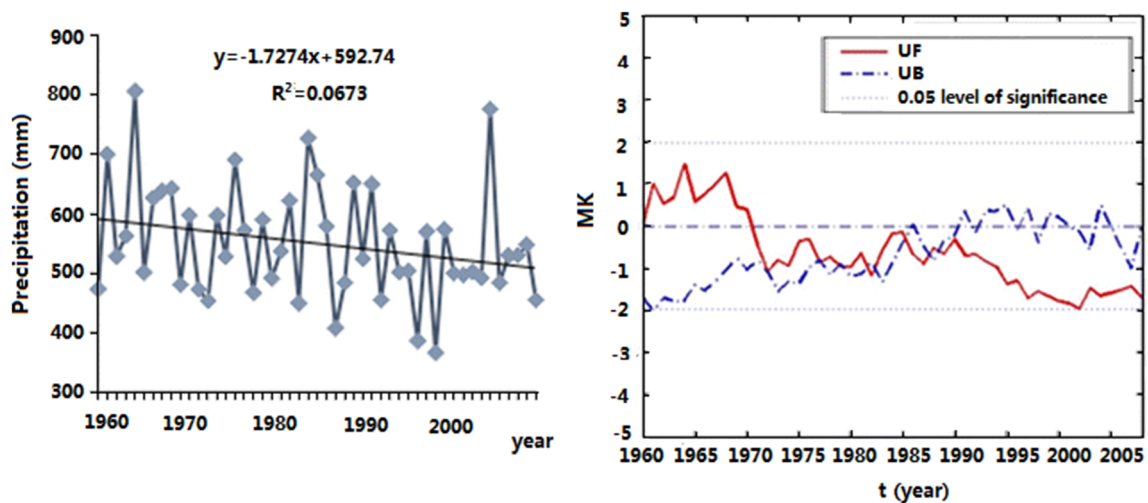
According to the results of Tables 4 and 5, after the transition year (1970), human activity played a dominant role in the sediment load and water discharge reduction in the WRB. The most important influencing factors of human activity leading to significant changes in the sediment load and water discharge were the soil and water conservation projects (e.g., reservoirs, bench terraces, afforestation and farmland in a check dam) in the WRB basin. Table 6 shows that the soil conservation area has expanded with time. At the end of 2010, the watershed conservation

projects had already covered a total area of 33,482 km², more than 24.83 % of the whole basin area. These soil conservation practices changed local micro-topography, intercepted precipitation, improved the infiltration rate of water flow, slowed down or retained the runoff and sediment load, and consequently delayed or even reduced runoff and sediment generation (Du and Shi 2012; Chang et al. 2015; Nadal-Romero et al. 2015; Zhou et al. 2013).

Moreover, tributary reservoirs have continued to increase from 1970 to 1990. These reservoirs redistributed the seasonal water discharge and sediment load within any given year and adjusted their interannual distribution. According to statistical data from the Ministry of Water Resources, 1635 diversion projects such as the Baojixia, Jinghuiqu, and

Table 6 Cumulative area of soil and water conservation in Wei River at the end of different years (Unit:km²)

River	Decades	Level terrace	Afforestation	Grass-planting	Check dam	Total
Main stream	1960s	844	764	163	8	1779
	1970s	2392	2596	303	23	5314
	1980s	3720	5744	1902	30	11,395
	1990s	6179	8608	2141	34	16,962
	2000s	8191	9875	2588	36	20,691
Jinghe River	1960s	50	184	11	4	249
	1970s	330	666	90	10	1096
	1980s	729	1520	169	18	2436
	1990s	2356	4135	1023	49	7563
	2000s	2907	4773	1146	52	8878
Beiluo River	1960s	80	360	19	12	472
	1970s	196	624	53	31	904
	1980s	308	1204	249	31	1792
	1990s	553	2181	483	52	3269
	2000s	708	2510	562	55	3913
The whole basin	1960s	974	1309	193	24	2500
	1970s	2918	3886	446	64	7314
	1980s	4758	8468	2320	78	15,623
	1990s	9088	14,924	3648	134	27,794
	2000s	11,806	17,158	4296	143	33,482

**Fig. 8** Observed annual precipitation and Mann–Kendall trend test

Luohuiqu projects, located upstream of the Linjiacun, Zhangjiashan and Zhuangtuo Stations, respectively, had been built by 2015. Additionally, 129 large, medium, and small (I) reservoirs were constructed in the WRB. The sediment load and water discharge at Xianyang Station showed a significant decline after 1970 because of the operation of the Shitouhe, Fengjiashan, and Jinpen Reservoirs.

Apart from the above measures, extensive irrigation, life and industrial water use, and sand extraction from the river beds were also the important factors of sediment load and

water discharge reduction. Over the period from 1965 to 2010 in Shaanxi Province, the population increased from 21.34 to 38.33 million. With an increasing population and increasing economic development, the water volume withdrawn increased sharply.

The impact of climate on water discharge and sediment load occurred mainly through precipitation. The annual observed precipitation of the WRB showed a decreasing trend, and the value of the regression slope was -1.72 (shown in Fig. 8). The result of the Mann–Kendall test

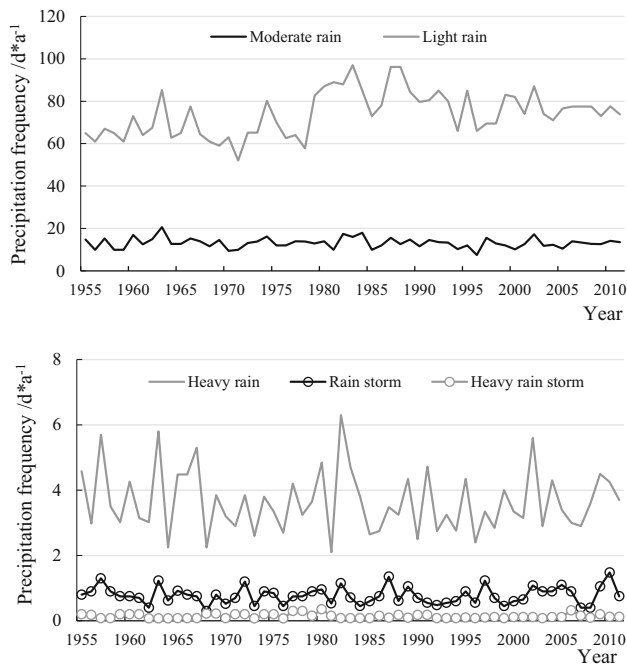


Fig. 9 Annual variation of precipitation frequency at different levels over the WRB

showed the same decreasing trend for annual precipitation in WRB from 1956 to 2010, although the trend was insignificant at the $\alpha = 0.05$ level. The annual precipitation in 1964 reached 805.5 mm, the highest in the last 50 years, and the lowest was only 367 mm in 1997. The decadal variability of precipitation indicated that 1956–1970 was a wet period. WRB suffered a long dry period from 1991 to 2000. The period of 1971–1980 was also a dry period. Then, the precipitation fluctuated from 1981 to 1990 near the long-term average value. From 2001 to 2006 was a wet period, where 2003 was the second highest year for precipitation in the last 50 years. The changes in precipitation with different levels were also analyzed according to the datasets of the long-term daily precipitation records of the 21 meteorological stations in the WRB. Thiessen polygons were used to calculate area-weighted average precipitation for the WRB. The daily precipitation levels were classified into the five following grades: light rain (0.1–9.9 mm), moderate rain (10.0–24.9 mm), heavy rain (25.0–49.9 mm), rain storm (50.0–99.9 mm), and heavy rain storm (100.0–249.9 mm). In the WRB, during 1956–2010, the days with more than 25 mm precipitation accounted for 2.28–7.31 % of the annual precipitation days, which occurred mostly in June, August, September, and October, and the precipitation value of these days accounted for approximately 60 % of the annual precipitation.

Figure 9 shows the annual variation in precipitation frequency at different levels over the WRB during 1956–2010. The change in precipitation frequency at different levels was

inconsistent. The precipitation frequency of light rain showed a significant increasing trend at the 5 % significance level, while the other precipitation frequencies exhibited decreasing trends, although all of the trends were insignificant. Significant increasing trends were found in the precipitation value of light rain and moderate rain, while the other levels of precipitation exhibited decreasing trends, and two of these trends were significant. The turning years of the precipitation frequency for light rain, moderate rain and heavy rain were, respectively, 1975, 1993 and 1971, and the turning years for the precipitation value of light rain, moderate rain, heavy rain and rain storm were, respectively, 1980, 1983, 1992, and 1981 (Liu et al. 2015).

Conclusions

Studying the variation in river sediment load and water discharge as well as river dynamic conditions is essential for the prediction of the future evolution of rivers and drainage basin management. In this paper, the variation of sediment load and water discharge in the WRB, and the relationship between sediment load and water discharge were analyzed by using statistical methodology. Additionally, the contributions of climate change and basin-wide human activities to the decreases were investigated.

The hydrology of the WRB is characterized by the major source areas of runoff that did not coincide with the major source areas of sediment. The lower reaches downstream supply approximately 73.72 % of the total river sediment load and only 47.54 % of the annual water discharge, especially in the tributaries of the Jinghe River and the Luohe River, where the water discharge is only 18.34 and 10.95 % of the total basin record, while the sediment load accounts for 56.70 and 19.85 %, respectively. The middle reaches contribute approximately 25.70 % of the water flow and generate no sediment.

The results of temporal and spatial changes in the annual sediment load and water discharge in the WRB showed that the water discharge and sediment load display significant decreasing trends. The changes were divided into the following three stages: the fluctuating stage (1956–1969), the slowly decreasing stage (1970–1979) and the accelerated decreasing stage (1980–2010), and water discharge decreased more quickly than sediment. An abrupt changing point was tested by using a double-mass curve, and the changes occurred mainly in 1970 and the late 1990s at most of the stations. The differences may be caused by the intervention of human activity and climate changes. Comparing the change ratio of the average annual water discharge and sediment load before and after a transition year shows that after the transition year, the reduction change scale of the average annual sediment load was more

significant. Spatially, the greatest reduction in water discharge and sediment load occurred upstream of the river. Additionally, the decrease in water discharge and sediment load on the main stream was greater than the decrease on the tributary. The relationship between average monthly water discharge and the sediment load shows a clockwise loop curve. The change points in the annual water discharge and sediment load relationship occurred mainly in 1983 for most stations.

We highlighted the contribution of the climate variability and human activity to water discharge and sediment load reduction. Human influences in the form of soil and water conservation projects and reservoir construction show their major impact on water discharge and sediment load variations. In addition to the relative contributions of human activity, precipitation variation may also be an important factor influencing runoff and sediment load changes, and their quantitative relationships require further investigation.

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