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Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China

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Abstract. Reduced stream flow and increased sediment discharge are a major concern in the Yellow River basin of China, which supplies water for agriculture, industry and the growing populations located along the river. Similar concerns exist in the Wei River basin, which is the largest tributary of the Yellow River basin and comprises the highly eroded Loess Plateau. Better understanding of the drivers of stream flow and sediment discharge dynamics in the Wei River basin is needed for development of effective management strategies for the region and entire Yellow River basin. In this regard we analysed long-term trends for water and sediment discharge during the flood season in the Wei River basin, China. Stream flow and sediment discharge data for 1932 to 2008 from existing hydrological stations located in two subcatchments and at two points in the Wei River were analysed. Precipitation and air temperature data were analysed from corresponding meteorological stations. We identified change-points or transition years for the trends by the Pettitt method and, using double mass curves, we diagnosed whether they were caused by precipitation changes, human intervention, or both. We found significant decreasing trends for stream flow and sediment discharge during the flood season in both subcatchments and in the Wei River itself. Change-point analyses further revealed that transition years existed and that rapid decline in stream flow began in 1968 ($P < 0.01$), and that sediment discharge began in 1981 ($P < 0.01$) in the main river. In the two subcatchments, the transition years were 1985 ($P < 0.01$) and 1994 ($P < 0.05$) for water discharge, and 1978 and 1979 for sediment discharge ($P < 0.05$), respectively. The impact of precipitation or human activity on the reduction amount after the transition years was estimated by double mass curves of precipitation vs. stream flow (sediment). For reductions in stream flow and sediment discharge, the contribution rate of human activity was found to be 82.80 and 95.56 %, respectively, and was significantly stronger than the contribution rate of precipitation. This evidence clearly suggests that, in the absence of significant decreases in precipitation, strategies for managing the region need to focus on human activities to control erosion without restricting stream flow.

1 Introduction

China's agriculturally important Loess Plateau, through which the Yellow River runs, is one of the most severely eroded areas in the world due to improper land use and excessive exploitation. Rivers in this region, e.g. the Wei River, transport a large amount of sediment to the Yellow River. Since the 1950s, many soil conservation measures to reduce sediment discharge and create water supply have been implemented in the Yellow River basin and associated basins, including the construction of terraces, dams and reservoirs, conversion of croplands to grasslands and woodlands, and vegetation restoration (Lee, 1984; Yu, 2006). As a result both sediment discharge and water flow have been significantly reduced. Meanwhile, the precipitation did not significantly decrease – not only in distinctive sub-basins but in the entire Yellow River basin (Ren, 2006; Yu, 2006; Fu et al., 2007; Mu et al., 2007; H. J. Wang et al., 2007; Gao, 2010). Although several existing studies verify that total amounts of stream flow and sediment discharge have decreased significantly in the Yellow River, scientific consensus on the magnitudes of the decreases and the quantitative effect of each driving factor (nature vs. human) has not yet been reached (Huang and Zhang, 2004; Mu et al., 2007; H. J. Wang et al., 2007). Fu et al. (2007) stated that climate variability had a significant impact on stream flow in the Yellow River and that stream flow was sensitive to both precipitation and temperature in the basin. H. J. Wang et al. (2007) and Gao et al. (2011) found that a decrease in precipitation is responsible for only 30 % of the decrease in stream flow and 20 % of the sediment discharge reduction, while the remaining 70 and 80 % are ascribed to human activities in the Yellow River basin. Better understanding of the relative impact of these driving factors, i.e. climate variation and human activity, on the hydrological regime and sediment dynamics in this region is needed for development of effective conservation strategies not only in distinctive sub-basins but also the entire Yellow River basin.

Most of the runoff in the Loess Plateau is generated by excess rain, which occurs during the many short-duration, high-intensity rainstorms in the flood season (June to September). Several studies indicate that a few intensive rainstorms in this time of the year produce most of the runoff and sediment. The sediment discharge in the flood season accounted for nearly 90 % of the total sediment for the year in the Wei River (Chen, 1996; Zhu et al., 2008). Therefore, in this study, we used data from the flood season to analyse the impact of climate change and anthropogenic activities on changes in stream flow and sediment discharge over the last 70 yr. We (a) identified trends and change-points for stream flow and sediment discharge in the flood season in two major subcatchments and the middle and downstream areas of the Wei River; (b) analysed the impacts of precipitation and/or human activities on the changes; and (c) estimated the relative effects of these main driving factors on both stream flow and sediment discharge by comparing two contrasting periods before and after the transition years. The findings of this study contribute valuable information for evaluation and implementation of long-term sustainable regional planning and land management.

2 Study area and data sets

2.1 Study area

The Wei River is the largest tributary of the Yellow River. It originates north of Niaosu Mountain in Gansu Province, flows about 800 km through Gansu and Shaanxi Province, across the Loess Plateau, and eventually into the Yellow River at Tongguan County. The whole basin is 135 000 km^2 in size. The two largest tributaries of the Wei River are the Jing River and Beiluo River which are also often considered to be major tributaries of the Yellow River. Traditionally this area is known as the Jing-Luo-Wei Region. We therefore included the two subcatchments containing these rivers, the Jing River subcatchment (45 421 km^2) and Beiluo River subcatchment (26 905 km^2) as well as the Wei River main stream in this study (Fig. 1).

2.2 Data sets

A data set compiled from 12 meteorological stations with long-term monthly precipitation data and annual air temperature data (1951–2008) in the Wei River basin was analysed (Fig. 1 and Table 1). This data was provided by The National Meteorological Information Centre (NMIC). Stream flow and sediment discharge data came from four hydrological stations within the Wei River basin, two key stations (Xianyang and Huaxian), located midway and downstream of the Wei River mainstream, and two stations in the Jing and Beiluo subcatchments (Zhangjiashan and Zhuangtou) (Fig. 1 and Table 1). Monthly stream flow and sediment discharge data at the four stations from 1932 to 2008 were obtained from the Chinese River stream flow and Sediment Communiques, the Ministry of Water Resources of PRC (People's Republic of China) (MWR). We also got the 1980 and 2005 land use data for the study region. The land use data was provided by the National Science and Technology Infrastructure Center, Data-Sharing Network of China Earth System Science (www.geodata.cn). ArcGIS was used to process the land use data. All measured data used in this study are of good quality and were checked for quality control by corresponding agencies.

3 Analysis methods

3.1 Selection of the flood season for data analysis

To determine the most important season for sediment discharge, we analysed the data from the four hydrological stations and selected the four months with the highest mean sediment discharge from 1932–2008.

Table 1. The location and data series of the hydrologic and corresponding meteorological stations.

Hydrological station	Meteorological station	Longitude (E)	Latitude (N)	Series (Monthly)
Xianyang		108°42′	34°19′	Stream flow: 1934–2008 Sediment discharge: 1934–2008
	Tianshui	105°45′	34°35′	1951–2008
	Xiji	105°43′	35°58′	1958–2008
	Baoji	107°08′	34°21′	1952–2008
	Wugong	108°13′	34°15′	1957–2008
Zhangjiashan		108°36′	34°38′	Stream flow: 1932–2008 Sediment discharge: 1932–2008
	Kongtong	106°40′	35°33′	1951–2008
	Huanxian	107°18′	36°35′	1953–2008
	Xifeng	107°38′	35°44′	1951–2008
	Changwu	107°48′	35°12′	1957–2008
Zhuangtou		109°50′	35°02′	Stream flow: 1933–2008 Sediment discharge: 1950–2008
	Wuqi	108°11′	36°50′	1957–2008
	Luochuan	109°30′	35°49′	1955–2008
Huaxian		109°46′	34°35′	Stream flow: 1934–2008 Sediment discharge: 1935–2008
	Tianshui	105°45′	34°35′	1951–2008
	Xiji	105°43′	35°58′	1958–2008
	Kongtong	106°40′	35°33′	1951–2008
	Baoji	107°08′	34°21′	1952–2008
	Huanxian	107°18′	36°35′	1953–2008
	Xifeng	107°38′	35°44′	1951–2008
	Changwu	107°48′	35°12′	1957–2008
	Wugong	108°13′	34°15′	1957–2008
	Xi'an	108°56′	34°18′	1951–2008
	Tongchuan	109°04′	35°05′	1955–2008

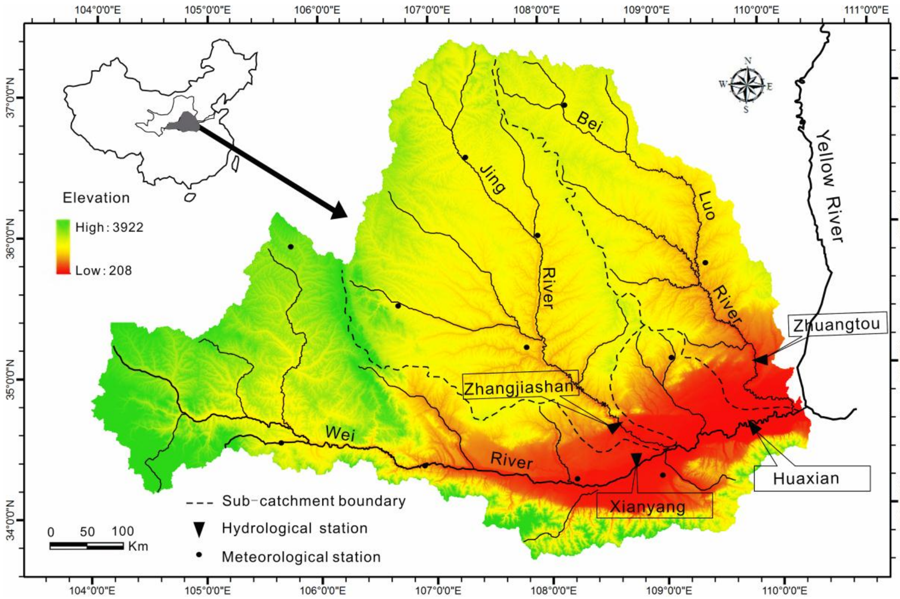

Fig. 1. Location of the study region and hydrological and meteorological stations in the Wei River basin.

3.2 Analysis of developments over time

Based on the results of Sect. 3.1, we analysed the development of precipitation, stream flow and sediment discharge in the flood seasons from 1932 to 2008 (discharge) and from 1951 to 2008 (precipitation), respectively, by the following methods.

3.2.1 Trend test to detect changes in time

To analyse the trends for precipitation, air temperature, stream flow and sediment discharge (Table 1) we used the rank-based, non-parametric Mann–Kendall statistical test (Mann, 1945; Kendall, 1975). This is commonly used for trend detection due to its robustness for non-normally distributed and censored data, which are frequently encountered in hydroclimatic time series (e.g. Hirsch et al., 1982; Burn and Elnur, 2002; Yue et al., 2003; Yue and Pilon, 2004; Gao et al., 2010). In this work the trend-free pre-whitening (TFPW) method of Yue et al. (2003) was used to remove any significant linear trend from the raw time series and serial correlation. A Z statistic was obtained from the Mann–Kendall test on the whitened series from TFPW method. A negative value of Z indicates a downward trend, and vice versa.

3.2.2 Change-point analysis to detect the transition year

We used the non-parametric approach developed by Pettitt (1979) to detect change-points in the air temperature, stream flow, and sediment discharge time series, as well as for the precipitation data. This method detects a significant change in the mean of a time series when the exact time of the change is unknown. The test uses a version of the Mann–Whitney statistic $U_{t,N}$, that tests whether two sample sets x_1, ... x_t and x_{t+1}, ... x_N are from the same population. The test statistic $U_{t,N}$ is given by

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^{N} sgn\left(X_t - X_j\right) \quad \text{for} \quad t = 2, \ldots, N \tag{1}$$

and

$$\begin{array}{l} \text{if } \left(X_t - X_j\right) > 0,\ sgn\left(X_t - X_j\right) = 1 \\ \text{if } \left(X_t - X_j\right) = 0,\ sgn\left(X_t - X_j\right) = 0 \\ \text{if } \left(X_t - X_j\right) < 0,\ sgn\left(X_t - X_j\right) = -1 \end{array} . \tag{2}$$

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The null hypothesis of the Pettitt's test is the absence of a change-point. The test statistic K_N and the associated probability (P) used in the test are given as

$$K_N = \max_{1 \le t \le N} \left|U_{t,N}\right|, \tag{3}$$

$$P \cong 2 \exp\left\{-6\left(K_N\right)^2 / \left(N^3 + N^2\right)\right\}. \tag{4}$$

3.2.3 Double mass curve to detect impact of precipitation and human activity

Double mass curve is a simple, visual and practical method, and it is widely used in the study of the consistency and long-term trend test of hydro-meteorological data. This method was first used to analyse the consistency of precipitation data in the Susquehanna watershed, United States, by Merriam (1937), and Searcy et al. (1960) made a theoretical explanation of it. The theory of the double mass curve is based on the fact that a plot of the two cumulative quantities during the same period exhibits a straight line so long as the proportionality between the two remains unchanged, and the slope of the line represents the proportionality. This method can smooth a time series and suppress random elements in the series, and thus show the main trends of the time series. Over the last 30 yr, the effects of soil and water conservation measures and land use/cover changes on stream flow and sediment have been analysed using the double mass curve method, with good results (Mu et al., 2010). In this study, double mass curves of precipitation vs. stream flow and precipitation vs. sediment discharge were plotted for two different periods (before and after change-point year) to estimate changes in regression slope (proportionality). In addition, the double mass curves were also used to quantify the overall efficiency of soil conservation measures before and after transition years, which was estimated by the change-point analysis

To estimate the relative impact of precipitation and/or human activity on the reduction of total stream flow and sediment discharge for the period after the transition years, the information on these two factors and precipitation before the transition years were used to establish regression equations, and to further extrapolate the cumulative stream flow and sediment discharge to 2008. Calculated cumulative water flow (R_c) and sediment discharge (S_c) were based on the assumption that environmental conditions, including human impacts in the basin, in the period before the transition years remained unchanged in the period after the transition years. The difference between calculated and observed stream flow and sediment discharge for 2008 is considered to be the cumulative amount which is impacted by human activities.

Putting the average precipitation data post the transition year into the regression equations, we can calculate the annual average stream flow (R_co) and average sediment discharge (S_co) after the transition year. The difference between the calculated annual average before and after the transition year is the amount which is impacted by precipitation. The difference between the calculated annual average and the observed annual average in the same period is the amount impacted by human activities.

Table 2. The transition matrix of land use change and total area of different land use in 2005 and 1980 in the Wei River basin (land use in km^2).

1980/ 2005	Forestland	Grassland	Dry farmland	Irrigated land	Residential	Water	Vegetation cover $< 5\,\%$	Total in 2005
Forestland	**19 909**	481	270	9.25	0.00	0.50	36.7	20 706
Grassland	357	**49 974**	701	21.5	1.00	8.25	2.50	51 065
Dry farmland	21.0	453	**45 004**	5.00	0.50	26.7	1.75	45 512
Irrigated land	4.75	78.7	28.2	**14 629**	0.75	40.7	0.75	14 783
Residential	23.0	17.0	373	181	**1304**	1.50	0.25	1899
Water	5.00	25.2	49.5	12.2	0.00	**823**	0.00	915
Vegetation cover $< 5\,\%$	0.75	0.75	2.75	0.00	0.00	0.00	**138**	142
Total in 1980	20 321	51 029	46 428	14 857	1306	901	180	135 022

Bold – no changes in 1980 and 2005; normal – land use changes in 1980 and 2005.

4 Results and discussion

4.1 Land use changes in Wei River basin

No significant land use changes took place in the Wei River catchment in 1980 and 2005 (Table 2 and Fig. 2). The total area has a size of 135 022 km^2. Comparing land use in 1980 and 2005, there was a net increase of 592 km^2 in residential areas (45 % of the total area for this land use in 1980), followed by forestland (385 km^2, 1.90 %), grassland (36 km^2, 0.07 %) and water and wetland (14 km^2, 1.58 %). In contrast, the area of dry farmland, irrigated land and desert decreased markedly. Dry farmland decreased 916 km^2 (1.97 % of the total area for this land use in 1980), followed by irrigated land (74 km^2, 0.50 %) and land with less than 5 % vegetation cover (37 km^2, 21 %).

4.2 Seasonal distribution of precipitation, stream flow and sediment discharge

The distribution of monthly precipitation, stream flow and sediment discharge is extremely uneven and mainly concentrated in the flood season (June–September) (Table 3). Precipitation in the flood season accounted for more than 60 % of the total precipitation for the year. Stream flow from June to September accounted for more than 50 % of total flow volume. And the sediment discharge in this period accounted for nearly 90 %. Therefore, the analysis of trends and change-points were based on data from June–September.

4.3 Long-term trends and change-point year for precipitation, stream flow and sediment discharge in the flood season

There was no significant trend for precipitation at the Huaxian, Zhangjiashan and Zhuangtou stations from 1951 to 2009. However, at Xianyang station, precipitation decreased significantly ($p < 0.05$). Stream flow and sediment discharge

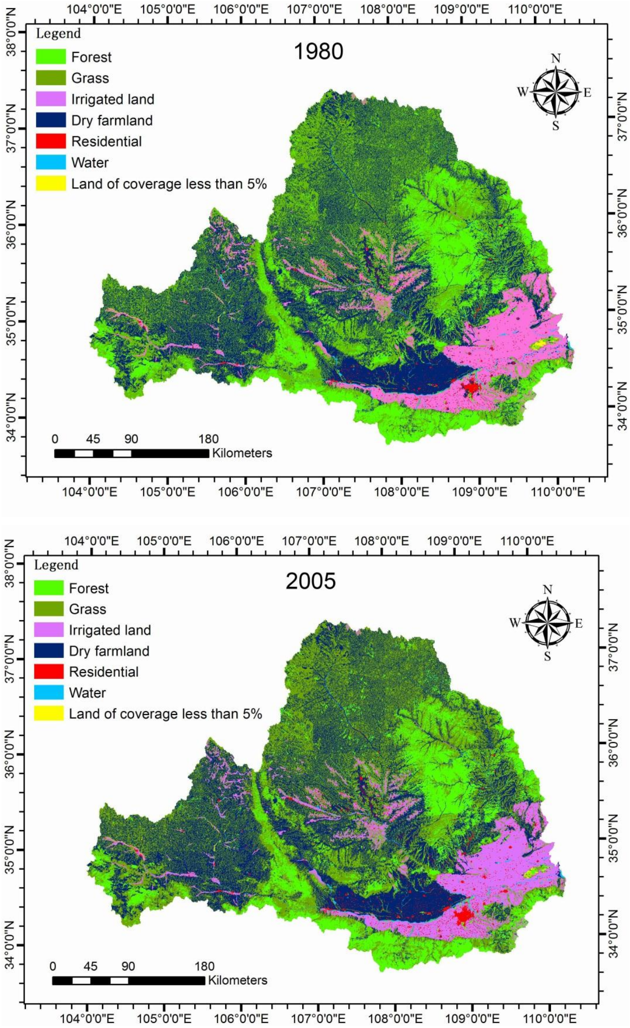

Fig. 2. Land use and cover of Wei River basin in 1980 and 2005 (the data is provided by the National Science and Technology Infrastructure Center, Data-Sharing Network of China Earth System Science, www.geodata.cn).

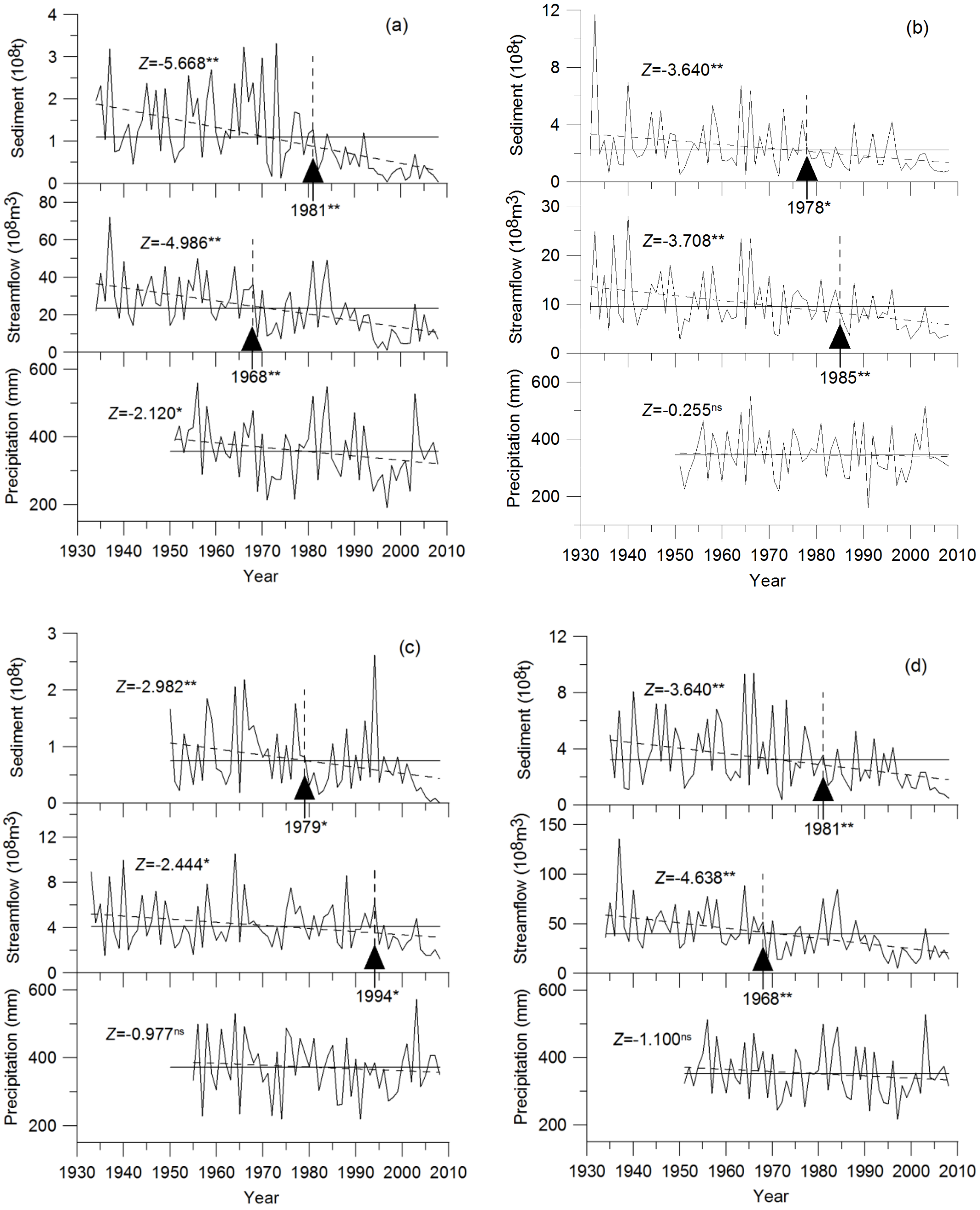

Fig. 3. Observed precipitation, stream flow and sediment discharge in the flood season (June–September) at: **(a)** Xianyang – Wei River middle station, **(b)** Zhangjiashan – Jing River, **(c)** Zhuangtou – Beiluo River, **(d)** Huaxian – Wei River downstream hydrological stations in the Wei River basin. The horizontal solid lines present the mean values for the flood season, the horizontal dashed lines indicate the trend line, the vertical dashed lines indicate the transition years, the Z statistic was obtained from the Mann–Kendall test (**: $p < 0.01$, *: $p < 0.05$, ns: not significant at $p \leq 0.05$).

on the other hand decreased significantly at all four stations from 1932 to 2008 (Fig. 3).

For stream flow, 1968 ($P < 0.01$) was the change-point year for the mainstream (Xianyang and Huaxian) stations, and 1985 ($P < 0.01$) and 1994 ($P < 0.05$) were the transition years for the Zhangjiashan and Zhuangtou stations, respectively.

For sediment discharge, the change-point year detected for the mainstream stations Xianyang and Huaxian was 1981 ($P < 0.01$). Transition years at the subcatchment stations

Table 3. Distribution of monthly precipitation, stream flow and sediment in the Wei River basin (P = mean precipitation, R = mean stream flow, S = mean sediment discharge).

Item		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Jun–Sep
Xianyang	P (mm)	5.2	7.8	19.5	39.4	55.5	65.8	98.6	99.0	93.4	50.4	16.2	3.9	554.6	356.9
	Percentage	0.9 %	1.4 %	3.5 %	7.1 %	10.0 %	11.9 %	17.8 %	17.9 %	16.8 %	9.1 %	2.9 %	0.7 %	100 %	64.3 %
	R (10^8 m^3)	1.3	1.2	1.6	2.6	3.5	3.0	5.8	6.0	8.7	6.6	3.1	1.6	45.0	23.6
	Percentage	2.8 %	2.6 %	3.5 %	5.7 %	7.8 %	6.6 %	13.0 %	13.4 %	19.3 %	14.6 %	6.9 %	3.6 %	100 %	52.4 %
	S (10^6 t)	0.1	0.1	0.6	2.2	5.1	10.1	35.3	42.3	21.9	6.3	0.8	0.1	124.9	109.5
	Percentage	0.1 %	0.1 %	0.5 %	1.8 %	4.1 %	8.1 %	28.3 %	33.9 %	17.5 %	5.1 %	0.6 %	0.1 %	100 %	87.7 %
Huaxian	P (mm)	5.3	7.7	19.0	37.0	52.7	62.0	103.6	98.7	87.7	47.8	16.8	4.2	542.6	352.1
	Percentage	1.0 %	1.4 %	3.5 %	6.8 %	9.7 %	11.4 %	19.1 %	18.2 %	16.2 %	8.8 %	3.1 %	0.8 %	100 %	64.9 %
	R (10^8 m^3)	1.9	2.0	2.7	4.1	5.5	4.6	10.1	11.1	14.1	10.9	5.2	2.6	74.8	39.9
	Percentage	2.6 %	2.6 %	3.6 %	5.5 %	7.4 %	6.1 %	13.5 %	14.8 %	18.8 %	14.5 %	7.0 %	3.4 %	100 %	53.3 %
	S (10^6 t)	0.2	0.2	0.8	3.5	9.9	19.5	114.2	133.6	53.9	12.2	1.6	0.3	350.0	321.3
	Percentage	0.0 %	0.1 %	0.2 %	1.0 %	2.8 %	5.6 %	32.6 %	38.2 %	15.4 %	3.5 %	0.5 %	0.1 %	100 %	91.8 %
Zhangjiashan	P (mm)	4.6	6.4	16.4	32.6	48.9	58.8	106.3	100.1	80.0	41.5	14.0	3.4	512.9	345.2
	Percentage	0.9 %	1.2 %	3.2 %	6.4 %	9.5 %	11.5 %	20.7 %	19.5 %	15.6 %	8.1 %	2.7 %	0.7 %	100 %	67.3 %
	R (10^8 m^3)	0.4	0.6	0.9	0.7	0.9	0.9	2.7	3.4	2.5	1.7	1.0	0.6	16.4	9.6
	Percentage	2.6 %	3.5 %	5.6 %	4.4 %	5.4 %	5.7 %	16.7 %	20.8 %	15.2 %	10.4 %	6.1 %	3.4 %	100 %	58.5 %
	S (10^6 t)	0.0	0.0	0.4	1.1	6.3	13.7	86.3	98.9	23.5	2.4	0.3	0.0	232.9	222.4
	Percentage	0.0 %	0.0 %	0.2 %	0.5 %	2.7 %	5.9 %	37.1 %	42.4 %	10.1 %	1.0 %	0.1 %	0.0 %	100 %	95.5 %
Zhuangtou	P (mm)	4.8	7.2	18.0	32.2	45.1	61.4	114.1	113.5	82.6	40.1	14.9	3.9	537.7	371.6
	Percentage	0.9 %	1.3 %	3.3 %	6.0 %	8.4 %	11.4 %	21.2 %	21.1 %	15.4 %	7.5 %	2.8 %	0.7 %	100 %	69.1 %
	R (10^8 m^3)	0.3	0.3	0.5	0.5	0.4	0.4	1.1	1.5	1.1	0.8	0.5	0.3	7.8	4.1
	Percentage	3.2 %	4.0 %	6.9 %	6.0 %	5.7 %	5.7 %	14.4 %	18.9 %	13.7 %	10.6 %	6.9 %	4.0 %	100 %	52.8 %
	S (10^6t)	0.0	0.0	0.1	0.2	0.8	3.8	29.0	33.5	7.5	0.8	0.0	0.0	75.7	73.8
	Percentage	0.0 %	0.0 %	0.1 %	0.3 %	1.1 %	5.1 %	38.3 %	44.2 %	9.9 %	1.1 %	0.0 %	0.0 %	100 %	97.4 %

were 1978 (Zhangjiashan station) ($P < 0.05$) and 1979 (Zhuangtou) ($P < 0.05$), respectively.

The trends and change-points for sediment discharge were very similar at all four stations and the transition years all ranged between 1978 and 1981. This indicates that the change in sediment discharge was similar throughout the whole basin. It also implies that the impact of external factors on the sediment discharge is consistent throughout the whole basin. However for stream flow, the change-point years are very different at the four stations. The transition year (1968) in the main river is 17 and 26 yr earlier than the transition years in the sub-basins (1985 and 1994 for the Jing and Beiluo rivers, respectively). Soil and water conservation measures (mainly focused on planting trees and grass) and agricultural irrigation were major human activities before the 1980s. Vegetation cut down the soil erosion effectively and reduced the sediment in the river. However, the influence of vegetation on runoff is much smaller than the sediment interception. Agricultural irrigation plays a major role in the stream flow reduction. The area around the main stream of the Wei River is the main grain-producing area for agriculture. More water diversion/extraction for large-scale irrigation in this area has caused the stream flow reduction in the main stream of Wei River since the 1960s. By contrast, the demand for and use of water in the subcatchment areas was lower and therefore there was a slower stream flow response. After the mid-1980s, the soil and water conservation engineering measures played a very important role in the stream flow reduction. These results also indicate that the impacts of human activity on sediment discharge and on stream flow are different.

4.4 The changes of the air temperature

There was a significant increasing trend for temperature in the Wei River basin from 1951 to 2008 ($P < 0.01$), and 1993 ($P < 0.01$) was the change-point year (Fig. 4). Previous studies have shown that the impact of temperature on the stream flow is uncertain. In some studies, the stream flow increased with increasing temperature (Fan et al., 2011); but in some other watersheds the stream flow decreased with increasing temperature (Cai and Cowan, 2008; Tang et al., 2012). In this study, the stream flow decreased with increasing temperature. In general, the air temperature change will affect evapotranspiration. According to the previous studies, in the middle reaches of the Yellow River, for every 1° rise in air temperature, watershed evapotranspiration will increase by 5–7 % (G. Q. Wang et al., 2007). In this study, the air temperature has risen by about 1° from 1951 to 2008, so, the evapotranspiration increased by 5–7 % in the Wei River basin.

4.5 Double mass curves of precipitation–stream flow and precipitation–sediment

Clear transition points can be identified between the two regression lines for both, stream flow and sediment discharge in the whole basin. The slopes of the regression lines were lower after the breakpoints, or transition years,

Table 4. Cumulative stream flow (R_c) calculated by the linear regression equations before the transition years, observed cumulative stream flow (R_o) and reduction of cumulative stream flow ($R_c - R_o$, 10^8 m^3 %) after transition years in the Wei River basin (N = years, P = precipitation).

Station	Regression equation	R_c (10^8 m^3)	R_o (10^8 m^3)	$R_c - R_o$ (10^8 m^3)	$100 \times (R_c - R_o)/R_c$ (%)
Xianyang	$R_C = 0.078 \sum P - 6.741$ ($R^2 = 0.99$, $N = 18$)	1603	1225	378	23.6
Zhangjiashan	$R_C = 0.030 \sum P - 4.523$ ($R^2 = 0.99$, $N = 35$)	590	508	82	13.9
Zhuangtou	$R_C = 0.012 \sum P - 2.428$ ($R^2 = 0.99$, $N = 40$)	238	215	23	9.6
Huaxian	$R_C = 0.131 \sum P + 6.043$ ($R^2 = 0.99$, $N = 8$)	2675	2084	591	22.1

Table 5. Cumulative sediment discharge (S_c) calculated by the linear regression equations before the transition years, observed cumulative sediment discharge (S_o) and reduction of cumulative sediment discharge ($S_c - S_o$, 10^8 t %) after transition years in the Wei River basin (N = years, P = precipitation).

Station	Regression equation	S_c (10^8 t)	S_o (10^8 t)	$S_c - S_o$ (10^8 t)	$100 \times (S_c - S_o)/S_c$ (%)
Xianyang	$S_C = 0.004 \sum P - 2.672$ ($R^2 = 0.99$, $N = 31$)	86.3	56.4	29.9	34.6
Zhangjiashan	$S_C = 0.008 \sum P - 2.459$ ($R^2 = 0.99$, $N = 31$)	148	121	27	18.4
Zhuangtou	$S_C = 0.003 \sum P - 0.682$ ($R^2 = 0.99$, $N = 25$)	51.5	40.1	11.4	22.2
Huaxian	$S_C = 0.011 \sum P - 4.578$ ($R^2 = 0.99$, $N = 31$)	220	171	49	22.1

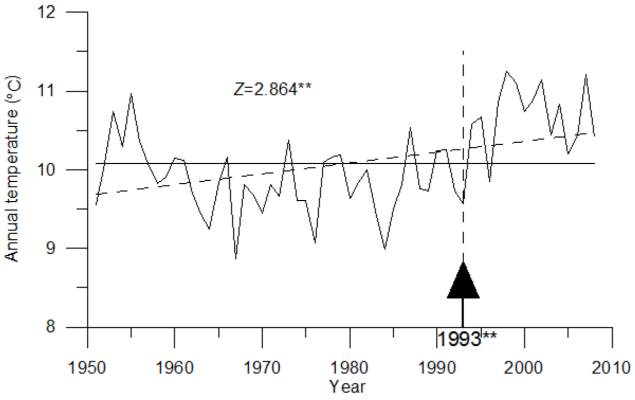

Fig. 4. Observed annual average temperature in the Wei River basin. The horizontal solid lines present the mean values for the flood season, the horizontal dashed lines indicate the trend line, the Z statistic was obtained from the Mann–Kendall test (**: $p < 0.01$).

than before for both stream flow and sediment discharge in the basin (Fig. 5). Compared with the calculated cumulative stream flow (R_c), observed cumulative stream flow (R_o) was reduced by 23.6, 13.9, 9.6 and 22.1 % at the Xianyang, Zhangjiashan, Zhuangtou and Huaxian stations, respectively (Table 4). The corresponding reduction for sediment discharge was 34.6, 18.4, 22.2, and 22.1 % at the four stations (Table 5).

It should be noted that the relative reductions in cumulative sediment discharge were greater than the relative reductions in cumulative stream flow. This may be caused by the fact that (a) reduced flow has much smaller sediment transport capacity and therefore increases chances for sediment deposition in the riverbed, and (b) most conservation measures, such as check dams, reservoirs, and conversion of croplands to grasslands, are more efficient in trapping sediment than water. All these factors seem more efficient in reducing sediment in drier years (Gao et al., 2009).

4.6 Impacts of precipitation and human intervention on stream flow and sediment discharge

We calculated the annual stream flow and sediment discharge for the period after the transition years using the regression equations established from the double mass curve of precipitation–stream flow and precipitation–sediment before the transition years. As previously noted, the difference between the calculated values before and after transition is the impact of precipitation changes. However, the difference between the calculated values and measured values in the post transition period is the result of human activities. The results are shown in Tables 6 and 7.

For stream flow reduction, the impact of human activities varied from 68 to 94 % at the four stations (Table 6), and has been the dominant factor ever since the transition year. The average human activities contribution rate for the entire area is 83 %, which is significantly higher than the average contribution rate of precipitation (17 %). Human activity was also the main factor in the sediment discharge decline after the transition year (Table 7). The average human activities contribution rate to reductions in sediment discharge is 95 % in the Wei River basin, which is very significantly

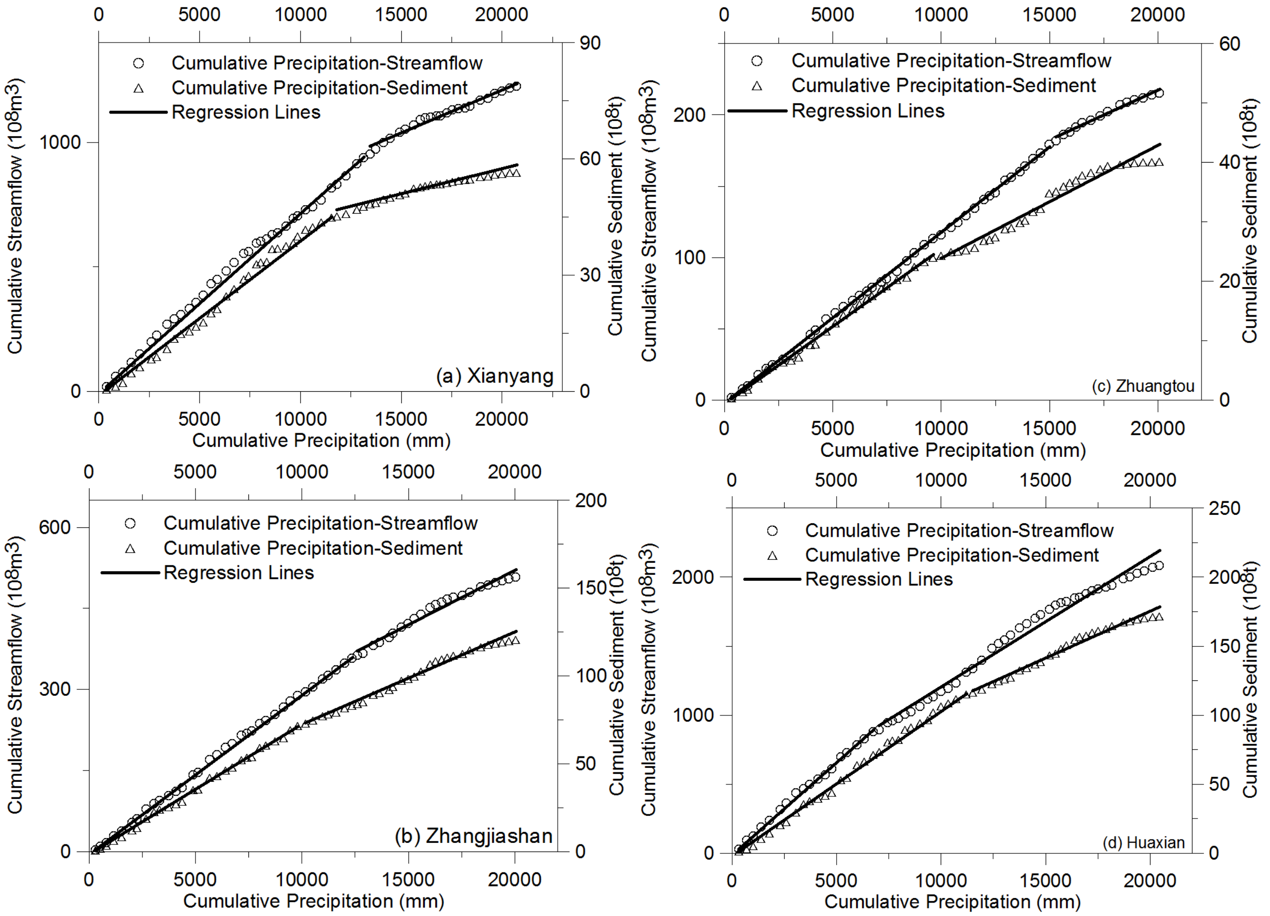

Fig. 5. Double mass curves of precipitation–stream flow and precipitation–sediment at: **(a)** Xianyang, **(b)** Zhanjiashan, **(c)** Zhuangtou and **(d)** Huaxian, in the Wei River basin. The straight lines are the regression lines for the cumulative data before and after change-point years.

higher than the contribution rate of precipitation (4.44 %). The analysis showed that human activities played a major role in both stream flow and sediment discharge reduction in the Wei River basin.

Many different human activities have had an influence on stream flow and sediment discharge in the Wei River. Land use did not change significantly between 1980 and 2005, which indicates that other human activities played the important roles on the reduction in stream flow and sediment yield, which can be outlined as follows.

First, increased demand for water resources in the Wei River due to economic development. The Wei River flows through the Guanzhong–Tianshui Economic Zone and this region is the fastest growing economic region in Gansu and Shaanxi Provinces. With the rapid economic development, water extraction and diversion has increased dramatically for agricultural irrigation and urban and industrial use. The average annual water extraction and diversion was $5.0 \times 10^8\,\mathrm{m}^3$ in the 1950s, and it has grown to $19.7 \times 10^8\,\mathrm{m}^3$ in the 1990s, accounting for 46 % of the average annual stream flow at the Huaxian station in the Wei River basin (Wang et al., 2008).

Second, construction of large/medium-sized multipurpose water control projects. These projects impact stream flow through evaporation and leakage losses from the reservoir and backwater areas. The major impact however is on sediment discharge, through siltation. Although undesirable, this has significantly reduced sediment discharge in the downstream regions. By 2000, there were 122 reservoirs with more than one million cubic meters of capacity in the Guanzhong region of Shaanxi Province. There is now about $2.75 \times 10^8\,\mathrm{m}^3$ of sediment deposition in the reservoirs, far exceeding the designed dead storage capacity of $1.77 \times 10^8\,\mathrm{m}^3$ (Shaanxi Province Department of water resources, 2000). The Sanmenxia reservoir, which was put into operation in 1960, caused the water level of Tongguan to increase, resulting in heavy sediment deposition in the lower reaches of the Wei River (Wang et al., 2005). From 1960 to 2000, about 13×10^8 t of sediment has been deposited in the lower reaches of Wei River (Li et al., 2003). Apart from

Table 6. The impact of precipitation and human intervention on stream flow decline after the change-point year at four stations in the Wei River basin (10^8 m^3 a^{-1}).

Station	Period	R_{ao}	R_{co}	ΔSR	Impact of precipitation	Impact of human intervention
Xianyang	Before 1968	30.73	30.65			
	After 1968	16.81	26.30	13.92 (45.30 %)	4.44 (31.86 %)	9.49 (68.14 %)
Huaxian	Before 1968	48.92	49.32			
	After 1968	30.09	44.68	18.83 (38.49 %)	4.24 (22.54 %)	14.59 (77.46 %)
Zhangjiashan	Before 1985	10.21	10.34			
	After 1985	6.55	9.92	3.66 (35.89 %)	0.30 (8.09 %)	3.37 (91.91 %)
Zhuangtou	Before 1994	4.48	4.43			
	After 1994	2.58	4.36	1.90 (42.54 %)	0.12 (5.86 %)	1.78 (93.68 %)

R_{ao}: observed annual average stream flow; R_{co}: calculated annual average stream flow; ΔSR: reduction in observed stream flow comparing with the period before the change-point year.

Table 7. The impact of precipitation and human intervention on sediment discharge decline after the change-point year at four stations in the Wei River basin (10^8t a^{-1}).

Station	Period	S_{ao}	S_{co}	ΔSS	Impact of precipitation	Impact of human intervention
Xianyang	Before 1981	1.45	1.51			
	After 1981	0.43	1.40	1.02 (70.38 %)	0.05 (4.62 %)	0.97 (95.38 %)
Huaxian	Before 1981	3.71	3.83			
	After 1981	2.09	3.65	1.63 (68.77 %)	0.06 (3.86 %)	1.56 (96.14 %)
Zhangjiashan	Before 1978	2.55	2.54			
	After 1978	1.64	2.52	0.91 (35.80 %)	0.03 (3.44 %)	0.88 (96.56 %)
Zhuangtou	Before 1979	0.96	0.97			
	After 1979	0.55	0.94	0.41 (42.22 %)	0.02 (5.86 %)	0.38 (94.14 %)

S_{ao}: observed annual average sediment discharge; S_{co}: calculated annual average sediment discharge; ΔSS: reduction in observed sediment discharge comparing with the period before the change-point year.

reservoirs, the "rainwater collection project" implemented in the Wei River has also contributed to stream flow and sediment discharge reduction since 1996. It was reported that 2 million small cisterns were built to collect storm water to provide drinking water for nearly 5 million people and irrigation for 3×10^3 km^2 in the dry season. Nearly 6×10^6m^3 of precipitation water has been collected each year, including the rainfall of precipitation events that did not produce runoff (Su et al., 2007), thereby reducing the amount of rainwater reaching the rivers.

Finally, soil and water conservation programs. The Loess Plateau is one of the worst soil erosion regions in the world, and the Wei River runs right through it. As noted, the Wei River is the largest tributary of the Yellow River, in terms of both stream flow and sediment discharge. The total area of soil erosion was 106 700 km^2 (including 39 700 km^2 around the Jing River and 21 540 km^2 around the Beiluo River), accounting for 79.2 % of the Wei River basin. Since the 1950s, a number of conservation measures have been implemented in the catchments of the Loess Plateau to control soil erosion and maintain agricultural productivity (Mu et al., 2007). These conservation measures include building terraces, sediment trapping dams, and changing land cover by replanting trees and improving pastures. By 2000, about 34 % of the erosion sensitive land was under protection through the implementation of various soil and water conservation measures. This included 16 370 km^2 of terraces, 1586 km^2 of farmland formed by sediment-trapping dams, 14 770 km^2 of soil and water conserving forest and 3734 km^2 of grass planting. The total area of soil and water conservation is now approximately 36 460 km^2. While these measures have been effective for reducing soil erosion, they have also resulted in noticeable changes in stream flow.

5 Conclusions

The overall results of our analysis show that human activities, such as economic development, soil and water conservation, and water projects, appear to be the important factors affecting the significant decrease in annual stream flow and sediment discharge in the Wei River basin that has occurred in recent decades. Further investigation of intervention and management strategies to control erosion without restricting stream flow will be of value to long-term sustainable management of the Wei River basin and the central Yellow River basin.

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