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Original Research Paper

Impact of Soil and Water Conservation Measures on Runoff and Sediment Environment in Wei River Basin

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ABSTRACT

The impact of the soil and water conservation measures in the process of river runoff and sediment discharge has caused wide attention. The Wei River, which has a serious water shortage and a high sediment concentration, was selected as the research watershed. Based on the measured data of rainfall, runoff and sediment, the statistical methods of wavelet analysis, Mann-Kendall test, and double cumulative curve were used to analyse the impact of soil and water conservation on runoff and sediment environment in Wei River Basin. The results showed that the river transported sediment increased during 1930s-1970s, and the average increasing rate was about 0.035×10^8 t/a. And the river transported sediment decreased after 1970s and the average decreasing rate was about 0.047×10^8 t/a. The relationship between water and sediment in Wei River Basin can be divided into two phases i.e., from 1940-1970s and after 1970s. From the 1940s to 1970s, there was less human activity, such as soil and water conservation, in the Wei River Basin, so the runoff and sediment yield changes were mainly affected by climate change. When the runoff was larger, the sediment load was larger and when the runoff was smaller, the sediment load was also smaller. After 1970s, large-scale measures of soil and water conservation were developed, which has great impact on soil erosion and sediment yield of basin and resulted in changing of laws between the runoff and sediment load. When the runoff was larger, the sediment load was smaller and when the runoff was smaller, the sediment load was also smaller, especially after 1997. It was concluded that the soil and water conservation play an important role in the reduction of the sediments of river. And when the comprehensive treatment reaches a certain level of governance, it has positive environmental benefits for both sediment and runoff.

INTRODUCTION

The measures of soil and water conservation have been used as agricultural production and to combat with floods and droughts. The protection of land resources is considered as the benefits of soil and water conservation and its impact on water resources are often overlooked in a very long period of time (Li et al. 2006). The decreasing of water and sediment discharge in rivers had a serious impact on the social, economic and ecological security, so it had caused a wide attention. The results of hydrological effects of soil and water conservation measures showed that, planting trees, grass, building terraces, dam and other measures gave the underlying surface covering of basin a great change, which reduce peak flows, increased the infiltration and runoff in dry season. And the hydrological effects were different in different geography and weather conditions (Li et al. 2007, Wang et al. 2009).

There is no consistent view about the impact of vegetation changes on the runoff in the basin at home and abroad (Li et al. 2001, Li 2001, Wei et al. 2005, Shao 2009). Some results showed that, increasing vegetation will increase runoff of the basin. Many results from former Soviet showed that the increasing of forest cover could improve the river flow and it was proved by citing large numbers of facts that the river level decreased and brought a drought due to deforestation (Li et al. 2001). The results studied in Moliesike, Gatilov, Volga of former Soviet showed that under the same climatic conditions, the annual runoff increased about 1.1mm when the rate of forest cover increased by 1% (Ma 1993). Bosch & Hewlett (1982) summary and review of 94 catchment experiments to get the effect of vegetation changes on the water yield showed that there was reduction in water yield with reduction in cover, or increase in yield with increase in cover, and the pine and eucalypt forest types caused on average 40-mm change in water yield per 10% change in cover and deciduous hardwood. In dryland areas of China, the analyses showed that with the increase of forest coverage, the peak flow reduced dramatically and the runoff in dry season increased (Wang & Zhang 2001). The comparative analysis of five watershed (674-5322 km^2) in the middle reaches showed that the annual runoff in multiple forest watershed was larger than that in less forest watershed, and the runoff coefficient increased by 33%-218% (Zhou et al. 2001). The monitoring results of 20 basins in Songhua River showed that, when the forest cover increased every 1%, the annual runoff would increase about 1.46mm (Sun 2001).

There are also many results showing that the increasing vegetation will decrease runoff of the basin. Liu and Zhong studied the influence of forest cover on the annual runoff in the middle reaches of the Yellow River and showed that the annual runoff in woodless areas was about 1.7 to 3 times than that in the wooded areas (Liu & Zhong 1978). It was determined that a forestland on the Loess Plateau reduced the total runoff, as a result of the increased retention of runoff and reduced recharged into groundwater (Li 2001). Two catchments of Switzerland were compared and the results showed that the flood flows and the annual water yield were smaller in the catchment with 99% of the forest than that in the catchment with 31% of the forest and 69% of the pasture (Engler 1919). Hibbert (1965) reviewed results from 39 catchment experiments throughout the world and showed that reduction of forest cover increases water yield. And some results showed that there was no relationship between the vegetation and the runoff (Li et al. 2001).

The terrace and check dams are effective measure to conserve soil and water conservation. Terrace in the main Weihe River basin could delay the flood and add the drought season runoff, prevent erosion and decrease river deposition, which were helpful for preventing soil and water loss and eco-environment improvement (Shao & Gao 2014, Shao et al. 2014). The results showed that the reduction of average annual flood account for 9.2% for the terraces measures in the Hezhong Town-Longmen Section in the middle reaches of the Yellow River from 1970 to 1996 (Ran et al. 2005). On the basis of investigation data of check dams in small watersheds in the hilly and gully region of Huangpuchuan, Kuyehe, Jialuhe, Tuweihe and Dalihe rivers on the Loess Plateau, the effect of check dams on sediment and water were analysed and the results showed that the sediment blocking benefit of the check dam ranged from 23.3% to 52.9% and the average benefits of water reduction was 5.74% (Jiao et al. 2003).

In a word, the soil and water conservation measures have a great influence on runoff and sediment environment. And their impacts were different in different areas, especially the vegetation measure. So the Wei River, which has a serious water shortage and a high sediment concentration, was selected as the research watershed, to study the impacts.

MATERIALS AND METHODS

Study Area

Wei River is the right branch of the Yellow River basin, which originates from the north of the Wushu mountains at an altitude of 3495 m, involves Gansu, Ningxia and Shaanxi Provinces, with a drainage area of about 134,766 km^2, and runs across 818 km before running into the Yellow River at Tongguan (Fig. 1) (http://www.sxsdq.cn/dqzlk/sxsz/slz/). The river goes across about 502.4 km and covers an area of about 67,100 km^2 in Shaanxi Province, where the well-known Guanzhong region of northwest China is located. It is the mother river of the Guanzhong region, which plays an important role in the development of west China (Song et al. 2007).

Acquisition of Data

Data used in this study include the daily rainfall data from 36 related stations of the Wei River basin, which includes 27 stations from portal of Chinese science and technology resource (http://www.escience.gov.cn) and 9 local rainfall stations of Shaanxi Province. The annual runoff and sediment data of 4 hydrological stations are from the Ecological Environment Database of Loess Plateau (http://www.loess.csdb.cn/pdmp/index.action) and hydrological yearbooks of China.

Methods

Wavelet analysis: Wavelet analysis is also called as resolution analysis, which originated in geophysics in the early 1980s for the analysis of seismic signals and was later formalized by Grossmann & Morlet (1984), Kumar & Foufoula Georgiou (1997) and Goupillaud et al. (1984). It is becoming a common tool for analysing localized variations of power within a time series. By decomposing a time series into time-frequency space, one is able to determine both, the dominant modes of variability and how those modes vary in time (Torrence & Compo 1998). The wavelet analysis has been used for numerous studies in geophysics for its advantages in signal processing (Wang et al. 2002, Xu et al. 2005, Shao et al. 2006).

The Morlet wavelet (Zhao et al. 2012) was used to study the periodic variation of rainfall and sediment of the Wei River and the wavelet function is as follows:

$$\psi(t) = \pi^{-1/4} e^{iw_0 t} e^{-t2/2} \qquad ...(1)$$

Where, t is the independent variable; w_0 is the non dimensional frequency, here taken to be 6 to satisfy the admissibility conditions.

The continuous wavelet transform of a discrete sequence *xn* is defined as the convolution of *xn* with a scaled and translated version of ψ0 (b):

$$W(a,b) = \sum_{b=0}^{n-1} X\Psi * \left[\frac{(b'-b)\delta_t}{a}\right] \quad ...(2)$$

Where the (*) indicates the complex conjugate; $W(a,b)$ is the wavelet coefficient; *a* is the wavelet scale and *b* is the localized time index; δ_t is the sampling interval.

Mann-Kendall trend test: This test is one of the commonly used non-parametric trend test (Hamed & Ramachandra Rao 1998, Liu 2011). It is derived from a rank correlation test for two groups of observations proposed by Kendall (Kendall 1946), and it is widely used for the assessment of significance of trends in many hydrologic and climatic time series (Yue & Wang 2004, Hamed 2008, Yu & Chen 2008, Hamed 2009).

The standardized test statistic *Z* (Ding & Deng 1988, Zhou 2005, Xu & Zhang 2006) is computed by:

$$U_{MK} = \frac{\tau}{[Var(\tau)]^{1/2}} \quad ...(3)$$

The test statistic τ defined as follows:

$$\tau = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(x_j - x_i) \quad sgn(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \quad ...(4)$$

$$Var(\tau) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \quad ...(5)$$

Where, x_j are the sequential data values; *n* is the length of the data set.

RESULTS AND DISCUSSION

The spatial variability and the time series trend of rainfall in Wei River basin: The Thiessen polygon method was used to analyse the annual rainfall data from 1956 to 2010. This method treats the area controlled by each rainfall station as weight to calculate the weighted average rainfall of the basin.

Fig. 2 is the spatial distribution of annual average rainfall from 1956 to 2010 in the Wei River watershed. It shows that the average annual precipitation has a significant geographical variation. The precipitation increases from 267 mm to 920 mm from northwest to southeast.

The average annual rainfall is 544.8 mm for nearly 60 years. From Fig. 3, we can see that the average rainfall of basin began a slight increase since 1956 and then it continued to decline gradually. It reduced to a minimum in 1990s and then began to increase subsequently.

The time series trend variability of runoff and sediment in Wei River basin: The Huaxian hydrological station is the outlet of Wei River, which changes in runoff and sediment and has a direct impact on the Yellow River. Fig. 4 is the time series of annual runoff and sediment at Huaxian hydrological station from 1935 to 2012. As can be seen, the changes in sediment load and runoff were synchronous with the rainfall trend before 1997, and after 1997, the runoff began to increase with rainfall increasing, but the sediment load still decreased. Even before 1997, the law between sediment and runoff was different. The maximum runoff was shown during 1935-1939, but the sediment load was only equivalent to the average value of 78 years. Different with the law during 1935-1939, the runoff decreased and the sediment load increased from 1940s to 1970s. There was a significant positive correlation between the amount of sediment and runoff, which changed with the rainfall variability. When the runoff was larger, the sediment load was also larger and when the runoff was smaller, the sediment load was also smaller. Compared to the 1970s, the runoff increased during 1980s and decreased during 1990s, while the amount of sediment reduced always. And there was no significant relationship between rainfall and sediment load during this time. The amount of sediment decreased significantly, although the runoff increased after 2000.

Fig. 5 is the time series of annual runoff and sediment at the Xianyang hydrological station of the middle reaches from 1934 to 2012. We also can see that the changes in sediment load and runoff were synchronous. And the runoff began to increase with rainfall increasing, but the sediment load still decreased after 1997. The relationship between the amount of sediment and runoff was also positive. The sediment load changed with the runoff. During the 1980s, the runoff was larger and the amount of sediment was smaller. And during the 1990s, the runoff decreased and the amount of sediment also decreased. After 2000, the amount of sediment continued to decrease, although the runoff began to increase.

Figs. 6 and 7 are the time series of annual runoff and sediment at Weijiabu and Linjiacun hydrological stations in the upper reaches. We also can see that there was a significant positive correlation between the amount of sediment and runoff from 1940s to 1970s. When the runoff was larger, the sediment load was also larger and when the runoff was smaller, the sediment load was also smaller. After 1970s, when the runoff was larger, the sediment load was smaller and when the runoff was smaller, the sediment load was also smaller [Sediment Discharge (10^8t), Runoff (10^8 m3), Time (year)].

The periodic variation of runoff and sediment in Wei

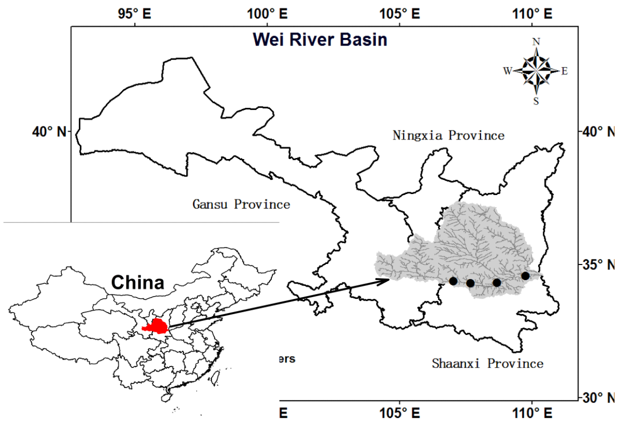

Fig. 1: The location and abridged general view of Baojixia under tableland irrigation area.

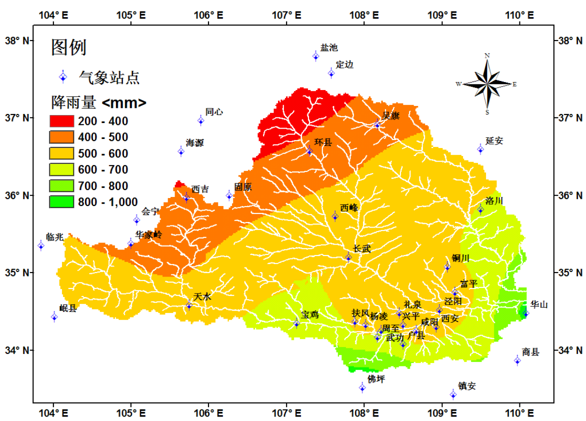

Fig. 2: The spatial distribution of annual average rainfall of Wei River watershed.

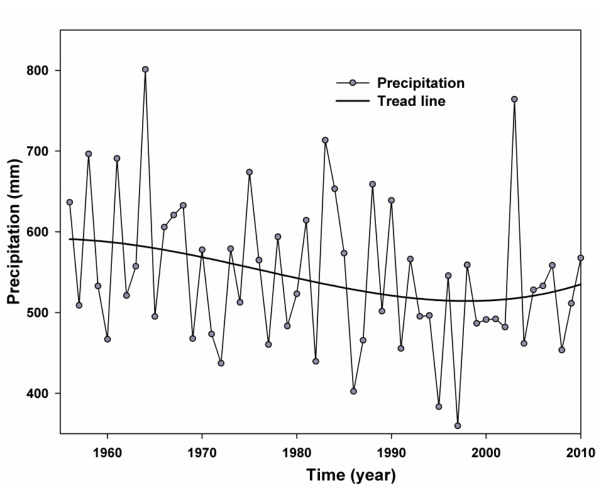

Fig. 3: The average annual rainfall for nearly 60 years of Wei River watershed.

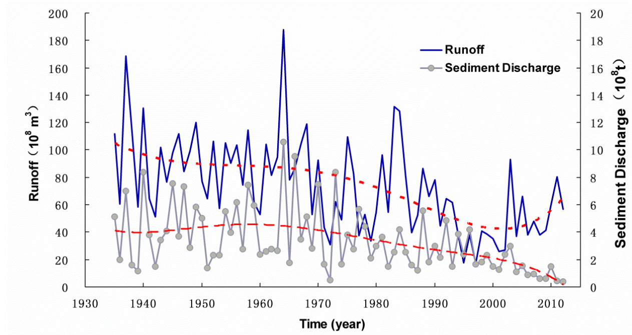

Fig. 4: The time series of annual runoff and sediment at Huaxian hydrological station.

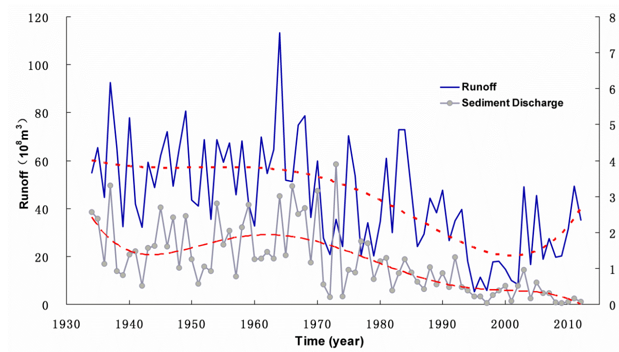

Fig. 5: The time series of annual runoff and sediment at Xianyang hydrological station.

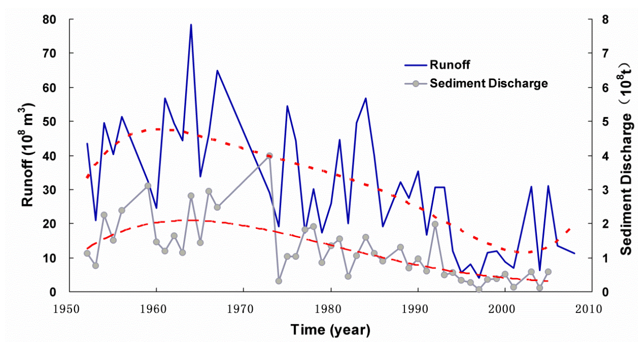

Fig. 6: The time series of annual runoff and sediment at Weijiabu hydrological station.

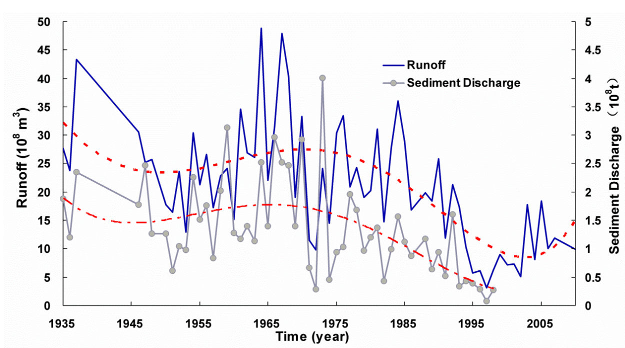

Fig. 7: The time series of annual runoff and sediment at Linjiacun hydrological station.

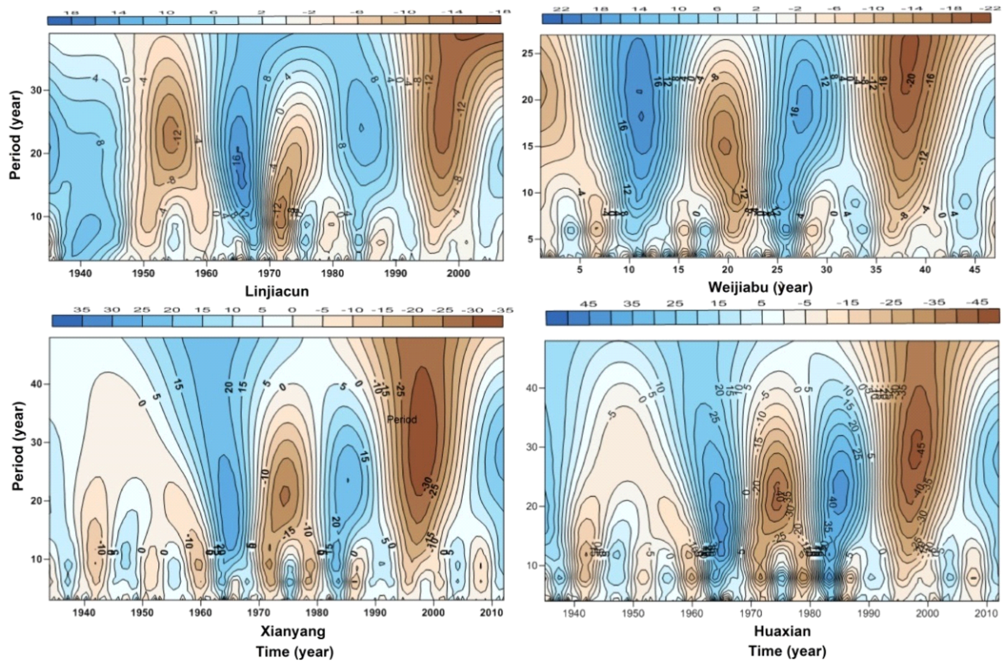

Fig. 8: The wavelet transforms of annual runoff for hydrological stations.

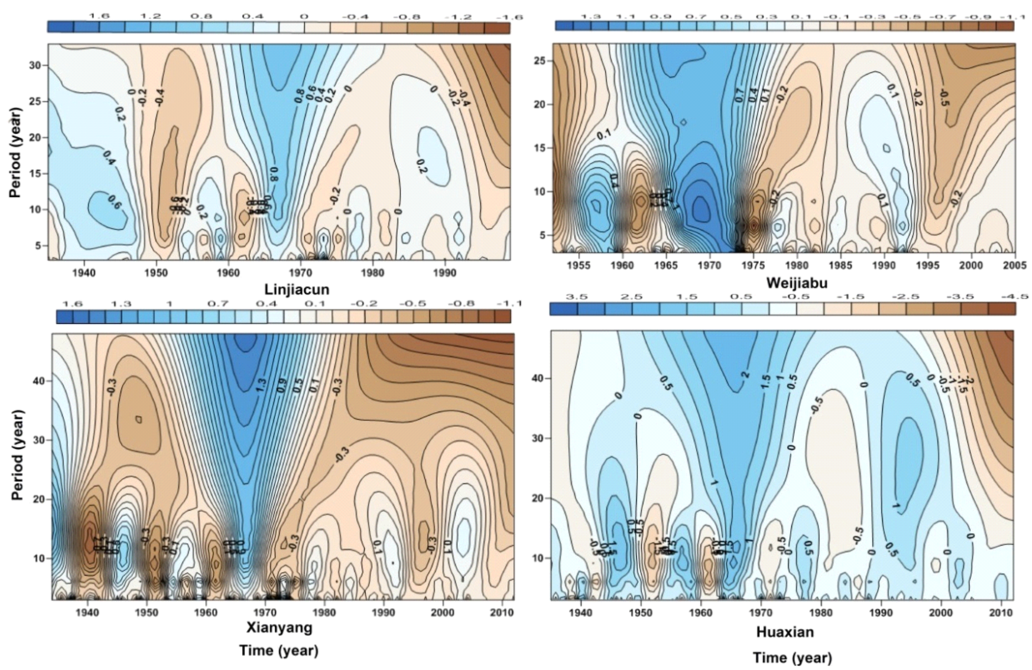

Fig. 9: The wavelet transforms of annual sediment for hydrological stations.

River basin: Fig. 8 is the result of wavelet transforms of annual runoff for Linjiacun, Weijiabu, Xianyang and Huaxian hydrological stations, showed the flow intensity distribution at different time scales. We can see that each station has a 20 to 25-year primary cycle, and the alternating between wet and dry years is evident. There was also an 8 to 11 year primary cycle at Xianyang and Huaxian hydrological stations in middle and lower reaches of Wei Rive,

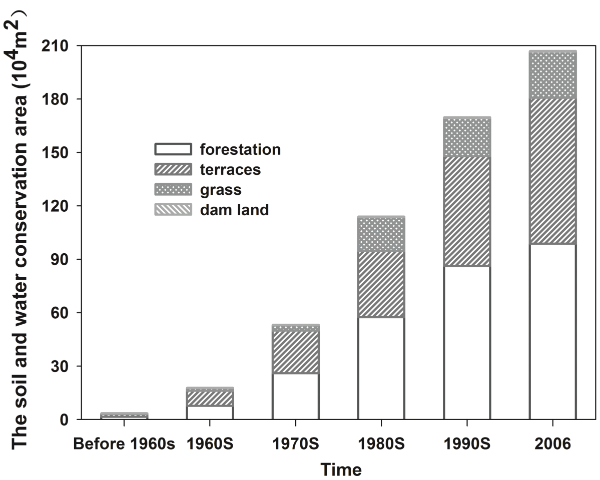

Fig. 10: The variability of different soil and water conservation measures at Main Stream basin of Wei River.

and the primary cycle was for shorter period before 1970s and it is gradually lengthened after 1970s.

Fig. 9 is the result of wavelet transforms of annual sediment yield for Linjiacun, Weijiabu, Xianyang and Huaxian hydrological stations, which showed the intensity of distribution of sediment yield at different time scales. As can be seen, the law of periodicity is not as strong as runoff, especially after the 1970s, the cyclical volatility reduced significantly. From the colour change and the wavelet coefficients, the sediment load reduced after 1970s.

The variability of soil and water comprehensive treatment in Wei River basin: Fig. 10 is the variability of governance areas of different soil and water conservation measures at main stream basin of Wei River. From the beginning of the 1970s, a large-scale soil and water conservation measures were implemented in the basin. The development area during 1980s was about 1.7 times larger than that during 1970s and 17.7 times larger than the cumulative implemented area before 1970s. The soil and water conservation area accounted for about 33.4% of the watershed control area until 2006.

At the same time, we can see that the forestation area was the largest, accounting for more than 43% of the total area of measures, followed by terraced steps, accounting for more than 33% of the total area. The dam land was the least, accounting for about 0.2%.

The impacts of soil and water comprehensive treatment on water and sediment environment: Based on the above analysis, the relationship between water and sediment in the Wei River basin can be divided into two phases: from the 1940s to 1970s, when the runoff was larger, the sediment load was larger, when the runoff was general, the sediment load was general, and when the runoff was smaller, the sediment load was also smaller; after 1970s, when the runoff was larger, the sediment load was smaller and when the runoff was smaller, the sediment load was also smaller, especially after 1997. In the previous stage, there was less human activity, such as soil and water conservation, water conservancy measures, in Wei River basin especially before the 1960s. So the runoff and sediment yield changes were mainly affected by climate change. At a later stage, large-scale measures of soil and water conservation and water conservancy were developed. Especially, measures of soil and water conservation have great impact on soil erosion and sediment yield of the basin, which resulted in changing of laws between the runoff and sediment load.

The double cumulative curve method was used to detect years of mutations for the relationship between annual runoff and sediment. Fig. 11 is the double cumulative curve

Table 1: The Mann-Kendall trend test of the annual sediment load for hydrological stations.

Station	Time	Zc	Tread	Significance level	Significance
Linjiacun	1935-1999	-4.087	Decrease	0.01	Significantly
Weijiabu	1952-2006	-4.813	Decrease	0.01	Significantly
Xianyang	1934-2012	-6.329	Decrease	0.01	Significantly
Huaxian	1935-2012	-4.56	Decrease	0.01	Significantly

Table 2: The quantitative monotonous trend of annual sediment load for hydrological stations.

Linjiacun station		Weijiabu station		Xianyang station		Huaxian station	
Time	β (10^8 t.a^{-1})	Time	β (10^8 t.a^{-1})	Time	β (10^8 t.a^{-1})	Time	β (10^8 t.a^{-1})
1935-1970	0.020	1952-1967	0.056	1934-1970	0.022	1935-1970	0.043
1935-1993	-0.016	1952-1993	-0.022	1934-1993	-0.016	1935-1993	-0.025
1935-1999	-0.023	1952-2005	-0.033	1934-2012	-0.022	1935-2012	-0.042
1970-1999	-0.041	1973-2005	-0.0461	1971-2012	-0.028	1971-2012	-0.074

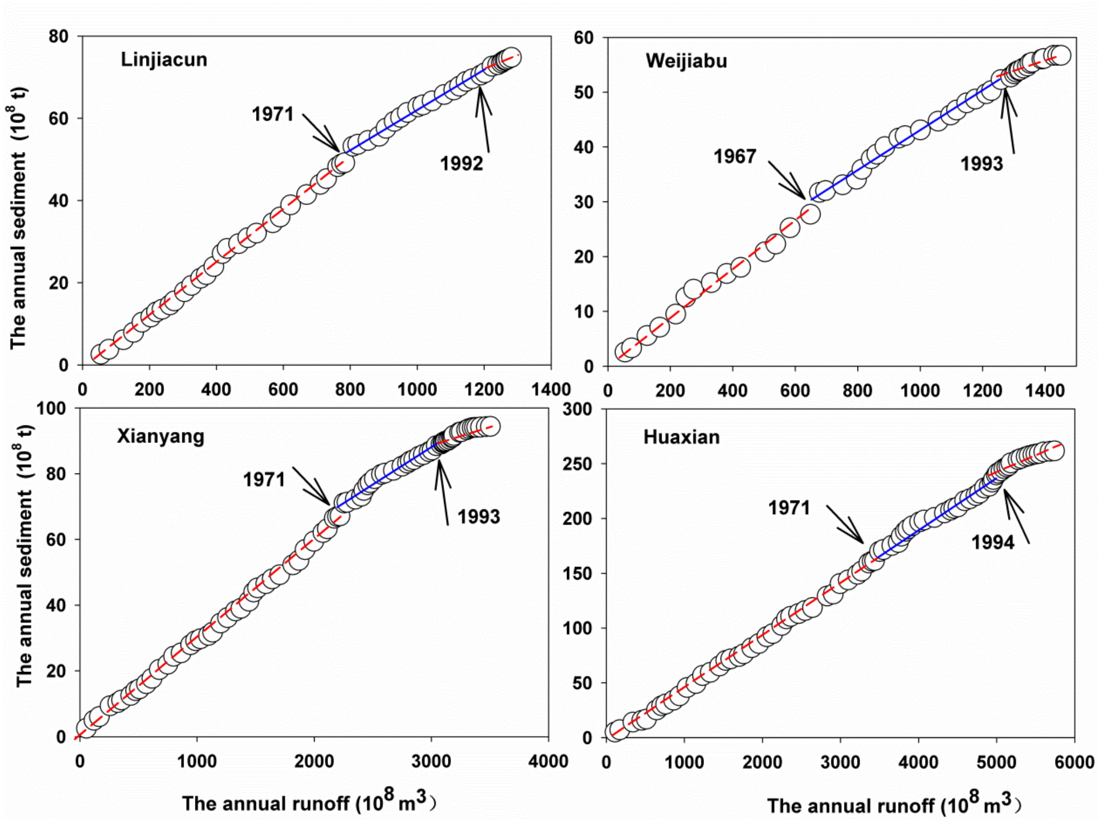

Fig. 11: The double cumulative curve between annual runoff and sediment.

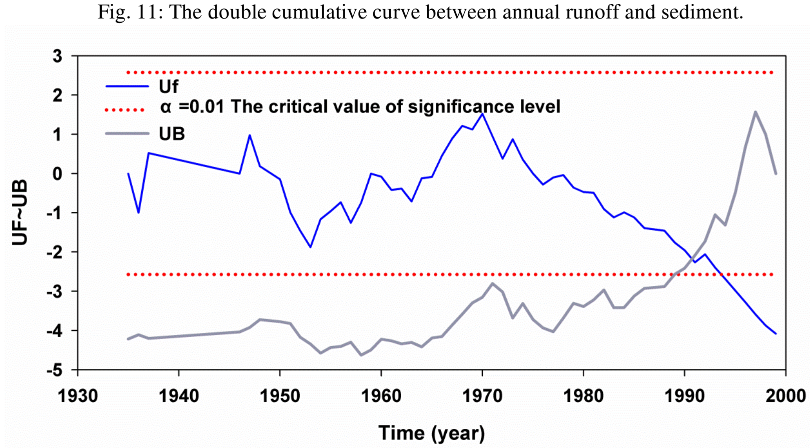

Fig. 12: The Mann-Kendall statistical test chart for the sediment amount of Linjiacun station.

between annual runoff and sediment for Linjiacun, Weijiabu, Xianyang and Huaxian hydrological stations. There are twice mutations of the relationship from the upstream to downstream of the Wei River. The first year was about 1971 (there was a lack of the sediment data at Weijiabu station during 1968-1972). And the second year was about 1993. These results were consistent with results studied in the Yellow River (Zhao & Mu 2012). The mutations were inseparable with large-scale measures of soil and water conservation from 1970s.

Fig. 12 is the Mann-Kendall statistical test chart for the amount of sediment at Linjiacun station. The figure shows that the amount of sediment has a significant decreasing trend at Linjiacun station, and 1992 was the year of mutation. Because the Mann-Kendall is good for the single mutation curve, this method was used only for trend test. The results showed that the sediment load decreased significantly at all hydrological stations and the significance was more than 99% (Table 1).

Based on the results of mutation analysis, the inclination β of Mann-Kendall to show the quantitative monotonous trend was calculated for Linjiacun, Weijiabu, Xianyang and Huaxian hydrological stations. The results showed that the statistic values of β at all stages in addition to 1970 and later were negative (Table 2). These results showed that the river transported sediment increased before 1970s. And the increasing rates were larger than 0.02×10^8 t/a. It was at the stage of soil erosion upswing for the population increasing and vegetation destruction. And the river transported sediment decreased after 1970s. The minimum value of β was at the Huaxian station during 1970-1999, which showed that this station has the fastest decreasing rate of sediment load, and the decreasing rates were about 0.074×10^8 t/a.

CONCLUSIONS

The large-scale comprehensive management in the Wei River basin has changed the land surface, which resulted in variation of basin infiltration, evapo-transpiration, runoff and other hydrological processes. Based on the measured data of rainfall, runoff and sediment, the statistical methods of wavelet analysis, Mann-Kendall test, and double cumulative curve were used to analyse the impacts of soil and water conservation on runoff and sediment environment in the Wei River basin.

The relationship between water and sediment in the Wei River basin can be divided into two phases: from the 1940s to 1970s, when the runoff was larger, the sediment load was larger, when the runoff was general, the sediment load was general, and when the runoff was smaller, the sediment load was also smaller; after 1970s, when the runoff was larger, the sediment load was smaller and when the runoff was smaller, the sediment load was also smaller, especially after 1997. During the previous stage, there was less human activity, such as soil and water conservation, water conservancy measures, in Wei River basin especially before the 1960s. So the runoff and sediment yield changes were mainly affected by climate change. At a later stage, large-scale measures of soil and water conservation and water conservancy were developed. Especially, measures of soil and water conservation has great impact on soil erosion and sediment yield of the basin, which resulted in changing of laws between the runoff and sediment load.

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