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Impacts of precipitation variation and soil and water conservation measures on runoff and sediment yield in the Loess Plateau Gully Region, China

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Abstract: The Loess Plateau of China has experienced a lengthy drought and severe soil erosion. Changes in precipitation and land use largely determine the dynamics of runoff and sediment yield in this region. Trend and mutation analyses were performed on hydrological data (1981–2012) from the Yanwachuan watershed in the Loess Plateau Gully Region to study the evolution characteristics of runoff and sediment yield. A time-series contrasting method also was used to evaluate the effects of precipitation and soil and water conservation (SWC) on runoff and sediment yield. Annual sediment yield declined markedly from 1981 to 2012 although there was no significant change in annual precipitation and annual runoff. Change points of annual runoff and annual sediment yield occurred in 1996 and 1997, respectively. Compared with that in the baseline period (1981–1996), annual runoff and annual sediment yield in the change period (1997–2012) decreased by 17.0% and 76.0%, respectively, but annual precipitation increased by 6.3%. Runoff decreased in the flood season and normal season, but increased in the dry season, while sediment yield significantly declined in the whole study period. The SWC measures contributed significantly to the reduction of annual runoff (137.9%) and annual sediment yield (135%) and were more important than precipitation. Biological measures (forestland and grassland) accounted for 61.04% of total runoff reduction, while engineering measures (terraces and dams) accounted for 102.84% of total sediment yield reduction. Furthermore, SWC measures had positive ecological effects. This study provides a scientific basis for soil erosion control on the Loess Plateau.

Keywords: Quantitative impact; Trend analysis; Evolution characteristics; Runoff and sediment yield; Rainfall; Land use change

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Introduction

Transport of water and sediment load from rivers to seas plays a key role in earth surface processes, and can induce dramatic geomorphological evolution in the river, estuarine delta and continental environment (Zhang et al. 2008; Dai and Liu 2013; Bastia and Equeenuddin 2016). Variations in river water discharge and sediment load have had profound impacts on catchment and estuarine delta developments, population and economic growth since the industrial revolution in the 18th century (Sadeghi et al. 2009; Davudirad et al. 2016; Li SS et al. 2016). Accordingly, a better understanding of the runoff and sediment yield changes and their potential driving forces is essential to improving the management of water resources and control soil erosion. In general, climate variability and human activities are identified as two important factors for changes in runoff and sediment yield (Mu et al. 2007; Zhang et al. 2012; Bao et al. 2012; Zhao et al. 2016). In recent decades, global climate variability has accelerated the hydrological cycle, thus changing the spatial-temporal variations of rainfall (Routschek et al. 2014; Zhao et al. 2015). This phenomenon has led to the increased occurrence of extreme meteorological events (especially rainstorm events), which directly or indirectly affect the regional runoff and sediment yield (Sadeghi et al. 2008; Li ZW et al. 2016). Large-scale human activities (such as SWC measures and land use change) affect runoff and sediment yield mechanisms by changing the underlying watershed surface conditions (Gao et al. 2013; Kong et al. 2015; Machowski et al. 2016). Soil and water conservation measures, such as afforestation, terraced construction and dam construction, are important ways to control soil and water loss and protect the ecological environment.

Assessments of the effects of human activities and climate change on hydrological processes are usually performed using experimental watersheds, hydrological models or statistical analysis (Son 2015; Zuo et al. 2016). The experimental watersheds method is traditionally used to measure the hydrological impacts of environmental change. However, it is vulnerable to restrictions of space and is less likely to consider the impact of climate change on hydrology (Brown et al. 2005; Archer 2007). Hydrological models, such as the Variable Infiltration Capacity (VIC), the Soil and Water Assessment Tool (SWAT) and the Xinanjiang model, have been widely applied to assess the impacts on hydrological regime under various scenarios (Kim et al. 2013; Zhang et al. 2015; Köylü and Geymen 2016). Although hydrological models can provide accurate results, a large number of parameters are difficult to directly measure and calibrate, and simulation results often have a degree of uncertainty. By comparison, statistical analysis is simple and the results have strong reliability; thus, statistical analysis has been widely used in water science research (Costa et al. 2003; Siriwardena et al. 2006; Guo et al. 2012).

The Loess Plateau Gully Region of China has long been considered a very fragile area that suffers from severe drought and water erosion, which not only seriously restricts the development of local society and economy, but also brings a series of ecological security problems to the lower reaches of the Yellow River (Ren et al. 2011; He et al. 2016; Wu et al. 2016). Since the 1970s, characteristics of runoff and sediment yield of the Yellow River have exhibited an obvious decreasing trend (Xu 2005). Changes in water flow and sediment in the Loess Plateau are closely related to the effects of climate change (such as precipitation) as well as to human activities (especially the implementation of SWC measures). At present, there are few studies on the effects of precipitation changes and water conservation measures on water and sediment variation at the watershed scale (Yan et al. 2013); however, related research in the gully region of the Loess Plateau is even rarer. Therefore, research on the variation of runoff and sediment yield, and on the effect that SWC measures have on changes in water flow and sediment in the watershed, is extremely significant for watershed soil erosion prediction and SWC benefit evaluation, particularly in the context of precipitation change.

The Yanwachuan watershed, located in Qingyang City, Gansu Province, is a typical meso-scale watershed of the Loess Plateau Gully Region. This watershed is one of the most serious soil erosion areas in China, so the variation of runoff and sediment yield in the watershed is representative of the response to precipitation changes and SWC measures in the region. To provide a scientific basis for comprehensive watershed management and sustainable development in the Loess Plateau Gully Region, this research examined changing trends of runoff and sediment yield from 1981 to 2012 in the Yanwachuan watershed. In addition, measures resulting in runoff changes and sediment reduction were analyzed systematically, and impacts of precipitation variation and SWC measures on runoff and sediment yield were evaluated.

1 Materials and Methods

1.1 Study area

Our study was conducted in the Yanwachuan watershed (107°37′–107°55′ E, 35°31′–35°44′ N), which covers an area of 366.95 km² with the surface elevation ranging from 945 m to 1448 m. The watershed is a nationally designated key management region for soil and water loss (Figure 1) and the soil erosion area accounts for 94.28% of the total watershed area. The study area belongs to the semi-humid monsoon climate zone with the average annual precipitation of 523 mm, of which about 80% occurs in the rainy season (May to September), and an annual mean temperature of 8.1°C. The watershed has three main geomorphic categories (tableland surface, gully slope and valley), which are the typical geomorphic characteristics of the Loess Plateau Gully Region. The geological structure is relatively singular, which is almost entirely covered by the Quaternary loess; thus, soil erosion is serious in this watershed. To curb serious soil and water loss, the Xifeng Experiment Station of Soil and Water Conservation selected the Yanwachuan watershed as a typical medium-sized watershed in the Loess Plateau Gully Region in 1975 and has since been carrying out various types of watershed management (Table 1).

Soil and water conservation measures in the Yanwachuan watershed were divided mainly into biological measures (planting trees and grass) and engineering measures (terraces and sediment-

Table 1 Areas of soil and water conservation measures implemented in the Yanwachuan watershed during 1981–2012 (Units: km²)

Year	1981	1989	1999	2004	2012
Forestland	7.08	25.85	81.10	88.42	107.32
Grassland	5.95	8.86	20.62	23.29	26.68
Terrace	18.51	34.85	84.57	92.79	103.07
Dam land	0.01	0.12	1.17	1.37	1.52
Total	31.55	69.68	187.46	205.87	238.59

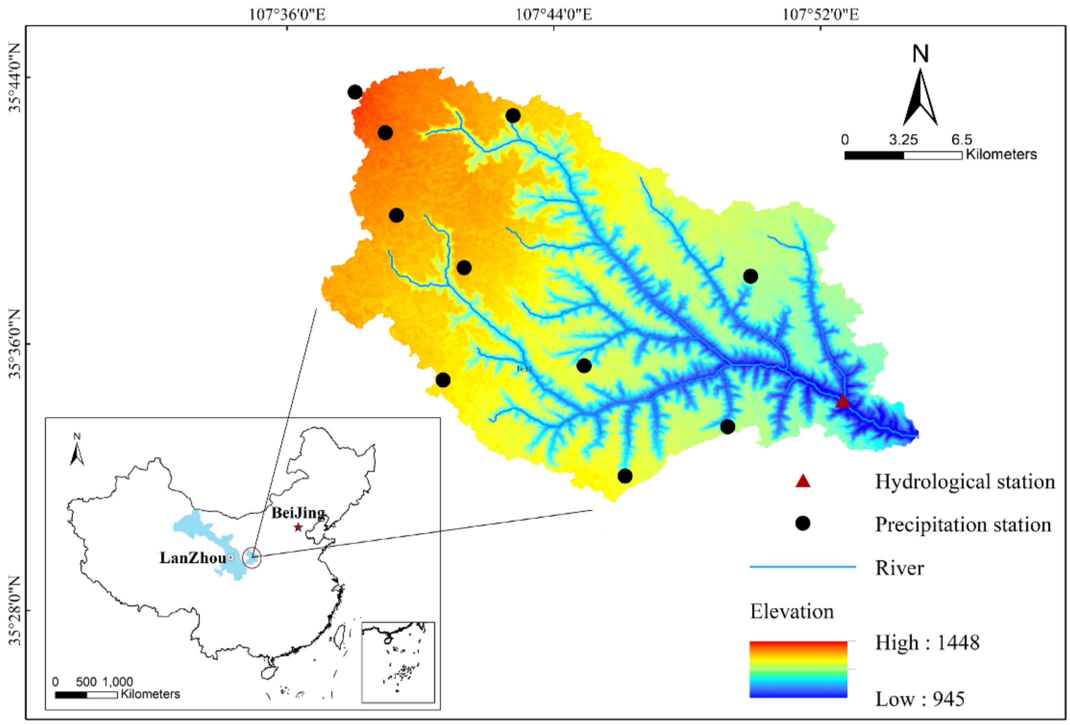


Figure 1 Location of the Yanwachuan watershed in China and distribution of rainfall stations.

trapping dams). During the 1970s to 1980s, small-scale conservation measures were carried out gradually and the area protected through comprehensive harnessing of SWC measures was very limited. However, large-scale SWC measures were implemented in the watershed since the early 1990s which greatly accelerated watershed management. By the end of 2012, 238.59 km^2 were in the management area of various SWC measures in the Yanwachuan watershed, which accounted for 68.96% of the total soil and water loss area (345.97 km^2).

1.2 Data monitoring and collection

We obtained the available data for the period 1981 to 2012 from the Xifeng Experiment Station of Soil and Water Conservation. Basic meteorological, hydrological, and SWC data were monitored and recorded at this station by automatic instruments.

(1) Rainfall data: There were 10 stations for long-term observations of rainfall in the study watershed; however, the Xifeng meteorological station close to the Yanwachuan watershed also had integrated rainfall data since 1937. The Yanwachuan station was the control station for the watershed (control area of 329 km^2). Areal precipitation was calculated using the Tyson polygon method.

(2) Runoff and sediment yield data: These data were all provided by the Yanwachuan station. A trapeziform trough was built at the outlet to collect real-time data. Each runoff and soil loss event was monitored by the trough during the rainy season. Events of different sizes were treated differently. For small rainfall events, the runoff was collected and measured in barrels. For severe rainstorms, runoff was calculated based on a marked buoy and flooding velocity measurement. For both situations, turbid water samples were collected with a measuring flask, and the samples were used to estimate water and sediment yield.

(3) SWC data: To reflect the status of SWC measures implemented in the study area accurately, we verified the statistical data concerning SWC measures through a field survey and with remote sensing data, thus identifying the actual area and distribution of various water and soil conservation measures.

1.3 Trend analysis and mutation test

1.3.1 Mann–Kendall test method

The Mann–Kendall (M-K) is a rank-based nonparametric method for assessing randomness against a time-series trend. It is a robust method to avoid the influence of extreme values, and is widely used to test the trend in meteorological and hydrological elements and their change points (Zhang et al. 2009; Birsan 2015; Sadeghi et al. 2015). In this study, the M-K test was used to detect the change in the annual precipitation, runoff and sediment yield. For a sample (x_1, x_2, ..., x_n) of the random variable x, the assumption of the null hypothesis is that the sample under investigation shows no beginning of a developing trend. The following test is performed to prove or to disprove this assumption, starting with calculation of a M-K test statistic, S_k:

$$S_k = \sum_{i=1}^{k} r_i, \quad k = 2, 3, \ldots, n \qquad (1)$$

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j \\ 0 & \text{otherwise} \end{cases} \quad j = 1, 2, \ldots, i \qquad (2)$$

Presuming that the series is random and independent, the definition of a statistics index UF_k is calculated as:

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}}, \quad k = 1, 2, \ldots, n \qquad (3)$$

in which $E(S_k)$ and $Var(S_k)$ are the mean and variance of S_k respectively; these can be calculated using the equation:

$$\begin{cases} E(S_k) = \dfrac{n(n-1)}{4} \\ Var(S_k) = \dfrac{n(n-1)(2n+5)}{72} \end{cases} \qquad (4)$$

UF_k follows the standard normal distribution. A positive Z-value denotes an upward trend and a negative Z-value denotes a downward trend, and if $|UF_k| > U_{\alpha/2}$ (where α is the significance level), the trend is considered to be significant (Zheng et al. 2014). While the forward sequential statistic UF_k is estimated using the original time series (x_1, x_2, ..., x_n), values of the backward sequential statistic UB_k are estimated in the same manner but starting from the end of the series. Plotting the results from Eqs. (1)–(4) (applying them both forwards and backwards) yields two curves UF_k and UB_k. If the intersection of the two curves occurs within a pre-determined confidence interval, an abrupt change is defined to have occurred at that point (Bai et al. 2014).

In the M-K test, another very useful index is the Kendall slope, which is defined as:

$$\beta = Median\left[\frac{x_j - x_i}{j-i}\right] \quad (5)$$

in which β is the median over all combinations of record pairs for the entire data set. A positive slope value denotes an increasing trend and a negative slope value denotes a decreasing trend.

1.3.2 Moving t-test technique

The moving *t*-test technique is used to test for a significant difference between the mean of two sample populations of a random variable for specified levels (Afifi and Azen 1972). This method can be combined with the Mann-Kendall mutation test, which is used to verify the authenticity of the mutation point detected by the Mann-Kendall mutation test method. Imagine that we have data on a continuous random variable X defined over two populations X_1 and X_2. Let μ_i, S_i^2 and n_i be the mean, variance and sample sizes, respectively, of X_i (i=1, 2). The null hypothesis is: H_0=μ_1−μ_2=0. Define the *t*-test statistic t_0 as:

$$t_0 = \frac{\mu_1 - \mu_2}{S_p\sqrt{(\frac{1}{n_1}+\frac{1}{n_2})}} \quad (6)$$

where the pooled variance S_p^2 is given by:

$$S_p^2 = \frac{(n_1-1)S_1^2 - (n_2-1)S_2^2}{n_1+n_2-2} \quad (7)$$

Under H_0, t_0 has Student's t distribution with n=n_1+n_2−2 degrees of freedom. Compare t_0 with t_α (where α is the significance level). If $|t_0| > t_\alpha$, the null hypothesis is rejected, that is, there is a significant difference between X_1 and X_2.

1.4 Separating the impacts of precipitation and SWC measures on the change in runoff and sediment yield

At present, the time series contrasting method is commonly used to evaluate the impacts of precipitation and SWC measures on streamflow and sediment yield. Although the methods used by different researchers are distinctive, these methods basically compare the baseline period (under natural conditions) and change period (influenced obviously by water conservancy and soil conservation measures) to calculate the effects of the two factors (Wei et al. 2015).

Therefore, the key to applying the time series analysis method is to determine the critical year that marks the end of the baseline period and the start of the change period. The double mass curve method, the correcting coefficient method and the empirical formula method are often used to estimate the contribution of climate change and human activities in recent years (Lorup et al. 1998; Li et al. 2007; Zhan et al. 2014). In our research, we used these three methods to analyze the effects of precipitation and SWC measures on changes of water and sediment in Yanwachuan watershed. The calculations were verified against each other.

(1) The double mass curve method requires two variables to occur in the same physical process, and portrays a cause-and-effect relationship (Mu et al. 2010). The slope of the double accumulative curve of annual precipitation plotted against annual runoff (sediment yield) was used to evaluate runoff and sediment yield changes qualitatively; that is, a change in the curve slope indicated that human activity changed the natural (or underlying) flow and sediment yield of the watershed. To make the double cumulative curve analysis quantitative, we determined the relationship between cumulative rainfall and cumulative runoff (cumulative sediment transport) using regression analysis on measured data collected during the baseline period. We then used cumulative rainfall values collected during the change period in this regression equation to calculate the cumulative runoff and cumulative sediment load values. Lastly, we compared the estimated values with the measured values to quantify the relative contribution of precipitation and SWC to runoff and sediment yield.

(2) The core of the correcting coefficient method is to ensure the ratio of runoff (sediment yield) during the baseline period to runoff (sediment yield) during the change period under the selected rainfall regime; that is, the runoff (sediment yield) correction coefficient of b_R and b_S

under the selected rainfall regime. Based on the above, the relation curves of $P—b_R$ and $P—b_S$ were plotted as the basis for correcting the runoff and sediment yield sequence during the change period. We obtained a corresponding correction coefficient on the relation curves of $P—b_R$ and $P—b_S$ according to rainfall of one year, and then multiplied the actual flow data (sediment transport value) by this correction coefficient to obtain the modified natural runoff (sediment transport). The differences before and after the correction are the changes caused by SWC measures.

(3) The empirical formula method is a commonly used method to calculate the effects of SWC measures on the runoff and sediment yield. The rainfall-runoff (rainfall-sediment yield) empirical statistical model is established based on annual precipitation data and annual runoff (sediment yield) data during the baseline period. Then, rainfall data collected during the change period are substituted into the model, and the annual runoff (sediment yield) given that the underlying surfaces should not be changed can be calculated. Thus, the difference between the estimated and measured data for runoff (sediment yield) caused by SWC measures are obtained.

2 Results

2.1 Trend and abrupt change analysis of hydrological factors in the watershed

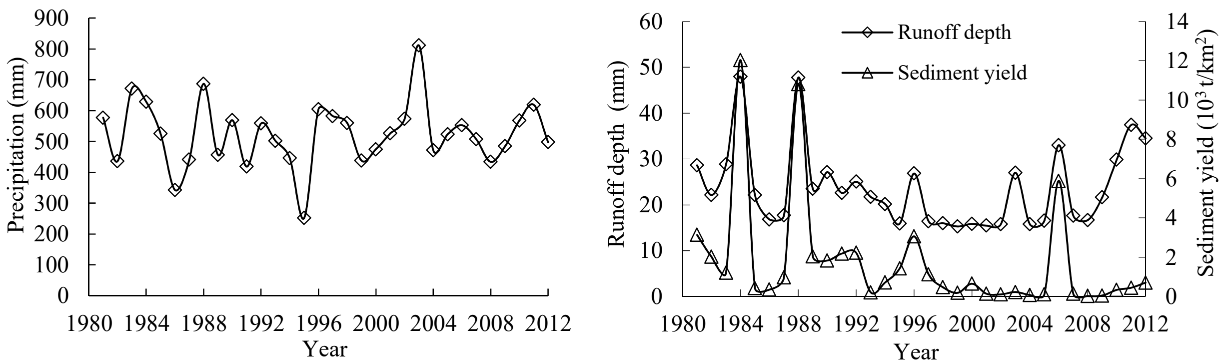
The changing trends of the annual precipitation, runoff and sediment discharge in Yanwachuan watershed are shown in Figure 2, while the results of the trend test are presented in Table 2. Figure 2a showed that there was no significant increase in the annual rainfall during the period 1981–2012. Annual runoff and sediment yield showed the decreasing trend during the study period; however, there were large differences in the changes over time, especially after 1997 when annual sediment yield remained stable while the runoff fluctuated greatly. In addition, annual runoff and sediment yield decreased under the increasing trend in annual rainfall, which indicates that changes in runoff and sediment yield may have been caused by the implementation of the water and soil conservation measures in the Yanwachuan watershed (Figure 2b).

Table 2 Results of trend tests for annual precipitation, runoff and sediment yield in the watershed

Observation terms	Statistic	Significance	Slope
Precipitation (mm)	0.27	NS	0.48
Runoff (mm)	-1.04	NS	-0.13
Sediment yield (10^3 t/km^2)	-3.47	*	-0.12

Notes: NS: Not significant. * indicates p < 0.05.

The analysis of annual precipitation and runoff trends (Table 2) showed that the statistical value of Mann-Kendall test for annual precipitation and runoff were 0.27 and -1.04 respectively, which were much smaller than the significance test value 1.96 with the confidence levels of 0.05; however, the statistical value of annual sediment yield was -3.47. Therefore, it can be seen that during the period of 1981–2012, the annual change in rainfall, which increased 0.48 mm/yr, was not obvious. Annual runoff exhibited no significant decreasing trend (declining 0.13 mm/yr), but the mean annual sediment yield decreased markedly (0.12 × 10^3 t/km^2/yr)(metric tons).



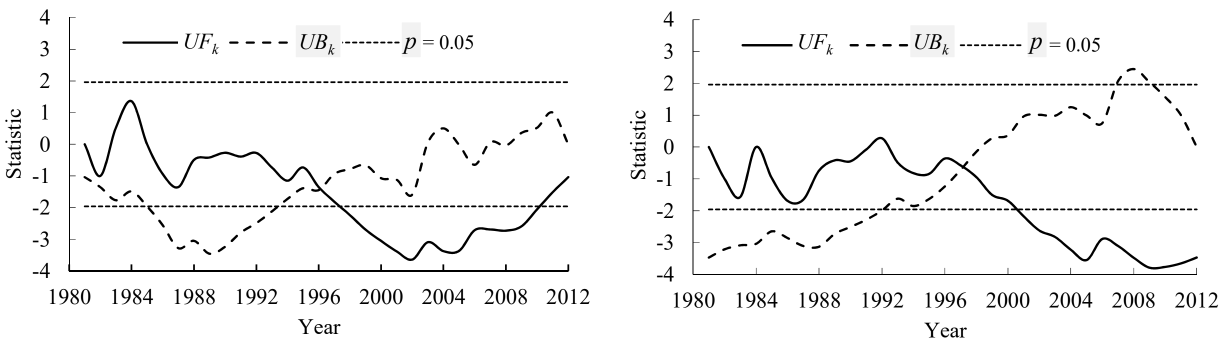
(a) Annual rainfall
(b) Annual runoff and sediment yield

Figure 2 The trends in (a) annual precipitation and (b) runoff and sediment yield in the Yanwachuan watershed.

Mutation analysis using the Mann–Kendall test (Figure 3) showed that abrupt changes in runoff and sediment yield occurred in 1996 and 1997, respectively, which were statistically significant at the 5% level, and that the two change points maintained a high degree of consistency. In 1994, implementation of SWC measures in the Malian River watershed as part of the World Bank loan project greatly accelerated watershed management in the Yanwachuan watershed; this development was in accord with timing of abrupt changes in runoff and sediment yield in the watershed. During the period 1981–2012, the UF_k value of annual runoff was less than 0 except in 1983 and 1984, which indicated that annual runoff showed a decreasing trend over the whole study period, but the trend was not significant. While annual sediment yield exhibited a decreasing trend since 1981, the trend was very noticeable during the period 2001–2012 when the average UF_k value was -3.212 and showed that the decreasing trend was very significant. This observation is consistent with the effect of implementing the policy of returning farmland to forest and grassland since 1999. The moving *t*-test method (6 year step) was used to further verify the abrupt change point of annual runoff and sediment discharge (Figure 4). Figure 4 showed that the change points in runoff occurred in 1995 and 1997 at the 5% significance level, and change points occurred in sediment yield in 1997 and 1998. The results of the two mutation test methods are basically the same: Abrupt changes in runoff and sediment yield occurred around 1997.

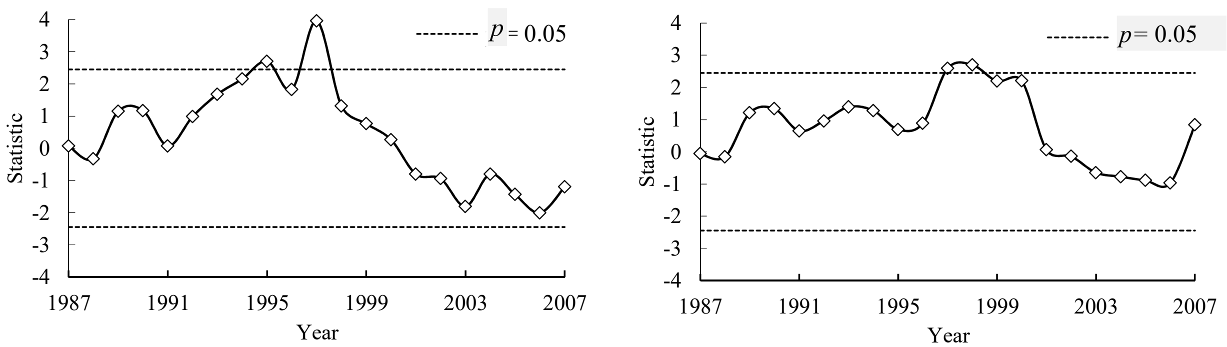
2.2 Evolution of hydrological factors

Based on the mutation analysis, corroborated by soil erosion control in the Yanwachuan watershed, the study period was divided into a baseline period (1981–1996) and a change period (1997–2012) to analyze the evolution of hydrological elements (Table 3). The mean annual precipitation during the baseline period was 507.1



(a) Annual runoff (b) Annual sediment yield

Figure 3 Change points of (a) annual runoff and (b) sediment yield for the Yanwachuan watershed (Mann-Kendall test method). UF_k, the curve of statistic of Mann-Kendall; UB_k, the curve of deserialized statistic of Mann-Kendall; *p*, significance level.



(a) Annual runoff (b) Annual sediment yield

Figure 4 Abrupt change of (a) annual runoff and (b) sediment yield for the Yanwachuan watershed (moving *t*-test method).

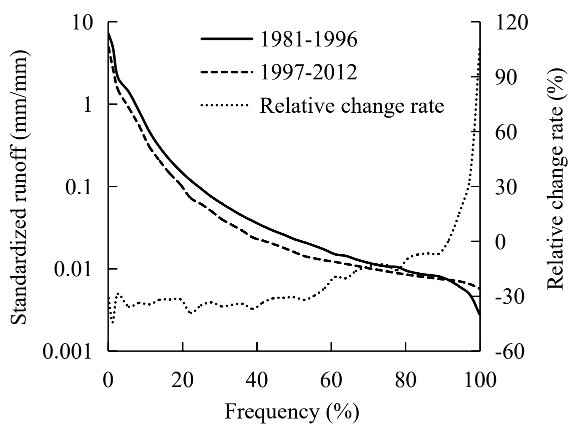
mm and increased by 6.3% to 538.9 mm during the change period; however, annual runoff and sediment yield decreased by 17% and 76%, respectively. In addition, the extreme ratio and variation coefficient of both annual precipitation and annual streamflow during the baseline period were greater than during the change period. However, annual sediment yield did not follow these trends due to the influence of heavy rain on 1 July 2006 in this area. Although the annual rainfall and runoff in 2006 were only 552.7 mm and 33.0 mm, respectively, the annual sediment transport modulus reached 5885 t/km², causing large fluctuations in the extreme ratio and dispersion coefficient of annual sediment yield during the change period.

The duration curves of runoff or sediment yield can well reflect the regime of streamflow or sediment yield (Mu et al. 2007). To eliminate the change in runoff or sediment yield caused by rainfall in different periods of time, we divided the daily runoff or sediment yield by the daily precipitation so that the effect of precipitation was standardized. Then we plotted the duration curves of runoff and sediment yield in the baseline and change periods using standardized daily runoff and daily sediment yield (Figure 5), and assigned frequencies of 5%, 50% and 95% to represent the wet, normal and dry season, respectively. As seen in Figure 5a, the flow duration curve was even flatter in the baseline period than in the change period, which indicated that the SWC measures caused the runoff change to be stable. Compared with the baseline period, runoff in the wet and normal seasons during the change period showed decreasing trends (decreasing by 35.7% and 30.4%, respectively), but increased by 20.5% in the dry season. Figure 5b shows that the sediment yield duration curve was steeper in the change period than in the baseline period, indicating that sediment yield decreased obviously during the change period. Furthermore, sediment yield decreased relatively less at frequencies below 20% in the change period, and the frequencies of sediment yield with a zero value increased by a large margin. Compared with the baseline period, sediment yield in the wet and normal season decreased by 85.2% and 100%, respectively, and decreased by 100% after the normal season. These results showed that soil erosion control in the Yanwachuan watershed already has demonstrated advantages in reducing flood volumes, compensating runoff and reducing sediment yield on the regional scale. These effects will become

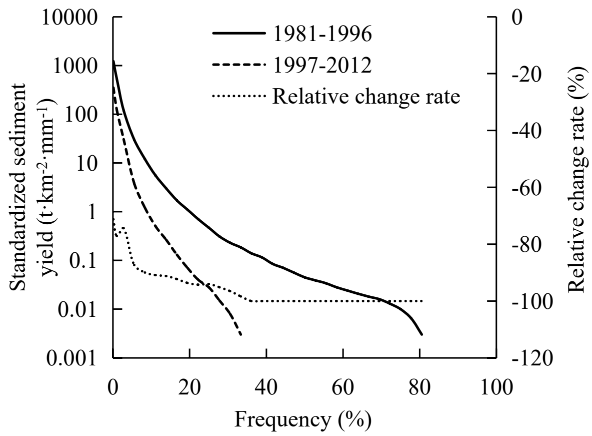
Table 3 Statistical description of hydrological factors during baseline and change periods

Observation terms	Baseline period (1981–1996)			Change period (1997–2012)			Relative change
	MV	E-R	VC	MV	E-R	VC	(%)
Precipitation (mm)	507.1	2.7	0.23	538.9	1.9	0.17	6.3
Runoff (mm)	25.9	3	0.37	21.5	2.4	0.36	-17.0
Sediment yield (10^3 t/km²)	2.79	57.3	1.27	0.67	196	2.03	-76.0

Notes: MV = Mean value; E-R = Extreme ratio; VC = Variation coefficient



(a) Duration curves of daily runoff



(b) Duration curves of daily sediment yield

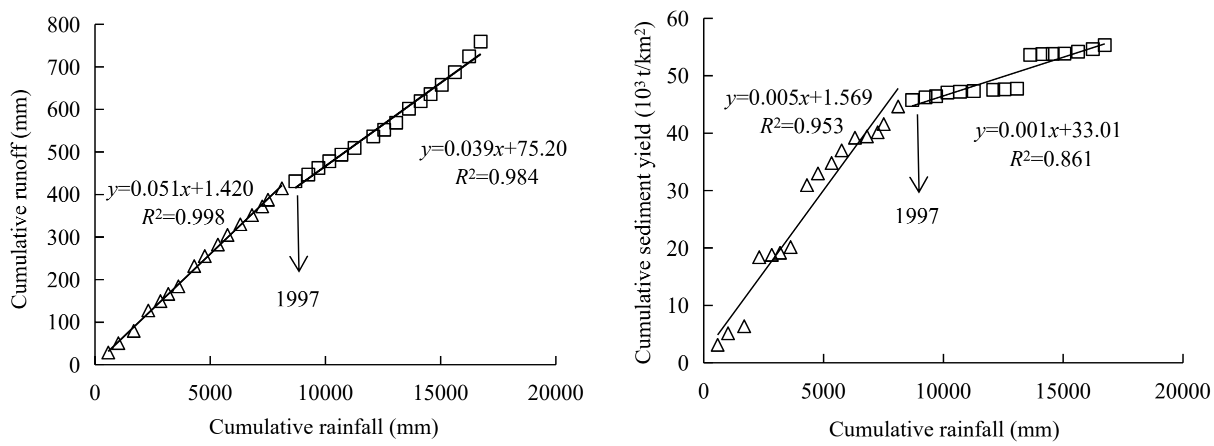
Figure 5 Duration curves of (a) daily runoff and (b) sediment yield during baseline and change periods.

more obvious over time.

2.3 Effects of precipitation and soil and water conservation measures on runoff and sediment yield in the watershed

As the basic principles of the three methods were almost the same, this paper focused on introducing the widely used double mass curve method to analyze the quantitative effects of SWC measures on runoff and sediment yield. In Figure 6, the cumulative annual runoff and sediment yield are plotted against the cumulative annual precipitation from 1981 to 2012 in the drainage watershed. The double mass curve will be linear if the annual runoff or sediment yield is only affected by the precipitation (except for extreme precipitation events), whereas a deflection from linearity shows that the underlying surfaces have changed. In general, the double accumulative curve of annual runoff and annual precipitation (Figure 6a) fluctuated slightly, and although the curve deviated to the right, the deflection degree was relatively small, indicating that a mutation of runoff occurred in 1997 but that the change range is small. The double accumulative curve of annual sediment yield and annual precipitation (Figure 6b) exhibited a large fluctuation, with very volatile changes in some years. The watershed rainfall that concentrated in 1984, 1988 and 2006 caused huge increases in sediment yield; in other words, the extreme precipitation events increased the fluctuation of the double cumulative curve. The curve deviated to the right in 1997, but after 1997 the curve is nearly horizontal, which indicated that the sediment yield was significantly reduced from pre-1997 levels. The deflection timing of the two double mass curves is consistent with the mutation test results.

By using the accumulated precipitation data (1997–2012) in the linear regression equation (developed using 1981–1996 data), we estimated the cumulative runoff and sediment yield that would have occurred in the absence of SWC measures. The difference between these estimated values and measured values can be attributed to the reduction of runoff and sediment yield caused by the SWC measures during the change period. These differences allowed us to estimate the relative contribution of precipitation and SWC measures on runoff and sediment yield variation. The results from the double mass curve method, correcting coefficient method and empirical



(a) Annual precipitation-runoff (b) Annual precipitation-sediment yield

Figure 6 Double mass curves for (a) annual precipitation-runoff and (b) annual precipitation-sediment yield from 1981 to 2012

Table 4 The impacts of precipitation change and soil and water conservation (SWC) measures on annual runoff and sediment yield change using three estimating methods

	Relative contribution to runoff change (%)				Relative contribution to sediment yield change (%)			
	DMC	CC	EF	Mean	DMC	CC	EF	Mean
Precipitation variation	-36.3	-31.9	-45.4	-37.9	-51.7	-29.2	-24	-35.0
SWC measures	136.3	131.9	145.4	137.9	151.7	129.2	124.0	135.0

Notes: DMC = Double mass curve; CC = Correcting coefficient; EF = Empirical formula

formula method are shown in Table 4.

There are some differences among the results from the three methods, but the results are close on the whole, and the difference is mainly caused by the fitting equation. During the period 1981–1996, the average annual runoff depth and annual sediment transport modulus were 25.9 mm and 2790 t/km², respectively. During the change period the mean annual runoff depth and annual sediment transport modulus were 21.5 mm and 669 t/km², respectively. Compared with the baseline period, the annual runoff depth in the change period decreased by 4.4 mm, and in this period, the contribution of water and soil conservation measures was 137.9% (decreasing runoff by 6.1 mm) while the contribution of precipitation change was -37.9% (increasing runoff by 1.7 mm). The annual sediment transport modulus decreased by 2121 t/km², to which the contribution of water conservation measures was 135% (reducing sediment transport by 2863 t/km²) and the contribution of precipitation change was -35% (increasing sediment transport by 740 t/km²). This showed that SWC management in the drainage watershed plays a great role in reducing runoff and sediment.

3 Discussion

3.1 Effect of soil and water conservation measures on runoff

Annual runoff in the Yanwachuan watershed showed a decreasing trend and a reduction of 17% compared with the baseline period. The relative contribution of water and soil conservation measures to runoff reduction was 137.9%. The duration curve of daily runoff after the late 1990s was flatter than previously, indicating that large-scale water and soil erosion control measures implemented in the watershed since the early 1990s had a stabilizing effect on runoff. Watershed management enhanced the underlying infiltration capacity, thereby reducing the tendency of rainfall being turned to runoff, which in turn affected the mechanism of yield and concentration of runoff and reduced flood volumes; therefore, runoff in the wet and normal season decreased. According to the flow duration curve, however, the runoff increased by 20.5% in dry season. The result is consistent with other relevant studies in the Loess Plateau region (Tang et al. 2010; Liu et al. 2015): Runoff in the wet and normal seasons showed decreasing trends, but increased in the dry season. As daily runoff data were standardized in the analysis to eliminate the effects of precipitation changes, runoff changes in the dry season were assuredly caused only by SWC measures. Low-flow runoff in the Yellow River Watershed occurs mainly in the dry season, and consists mainly of base flow; however, SWC measures, especially the increase of forest area and the construction of check dams, played a great role in the recharge of base flow.

3.2 Analysis of contribution of water and soil conservation measures to runoff and sediment yield reduction

Combining biological measures with engineering measures to control soil and water loss at the watershed scale is a prominent feature in the comprehensive management of soil and water loss in the Loess Plateau region. The research of Ran et al. (2006) showed that changes in the configuration of a system of soil and water conservation measures (terraces, dams, afforestation and grass planting) have an important influence on the reduction of sediment yield in a watershed. We used the SWC information to calculate the effects of SWC measures on runoff and sediment yield reduction (Table 5). For forestland, grassland and terrace, we used each SWC measure index of runoff (sediment yield) reduction to multiply by corresponding area to obtain the effects on runoff (sediment yield) reduction; for dam land, we directly utilized observation and measurement data to calculate runoff (sediment yield) reduction. Moreover, the benefits of water reduction and sediment reduction of various water and soil conservation measures were compared to analyze the relative contributions of biological and engineering measures to changes of runoff and sediment yield (Table 6).

The average annual runoff was 7088 × 10³ m³ during 1997–2012 in the Yanwachuan watershed, which was an annual reduction of 1438 × 10³ m³ in the 8526 × 10³ m³ of runoff during the baseline period. SWC measures reduced the annual runoff

Table 5 Reductions in runoff and sediment yield due to various soil and water conservation (SWC) measures in the Yanwachuan watershed

SWC measures	Baseline period (1981–1996)					Change period (1997–2012)				
	Area (km^2)	IRO (10^4 m^3/km^2)	ISY (10^4 t/km^2)	RO (10^4 m^3)	SY (10^4 t)	Area (km^2)	IRO (10^4 m^3/km^2)	ISY (10^4 t/km^2)	RO (10^4 m^3)	SY (10^4 t)
Forestland	35.42	1.36	0.203	48.17	7.19	93.15	1.36	0.203	126.68	18.91
Grassland	12.91	1.11	0.176	14.33	2.27	21.25	1.11	0.176	23.59	3.74
Terrace	50.04	1.44	0.433	72.05	21.67	91.54	1.44	0.433	131.82	39.64
Dam land	0.58	-	-	28.55	18.26	1.32	-	-	45.53	72.04

Notes: IRO = Index of runoff reduction; ISY = Index of sediment yield reduction; RO = Runoff reduction; SY = Sediment yield reduction

Table 6 Relative contributions of biological measures and engineering measures to reductions in runoff and sediment yield

Runoff and sediment yield reduction	Biological measures			Engineering measures			Total
	Forestland	Grassland	Subtotal	Terrace	Dam land	Subtotal	
Runoff reduction (10^4 m^3)	78.51	9.26	87.77	59.77	16.98	76.74	164.51
Sediment yield reduction (10^4 t)	11.72	1.47	13.19	17.97	53.78	71.75	84.94
Proportion of runoff reduction (%)	54.61	6.44	61.04	41.57	11.81	53.38	114.42
Proportion of sediment yield reduction (%)	16.80	2.11	18.90	25.76	77.09	102.84	121.75

by 1645.1 × 10^3 m^3, accounting for 114.42% of the total runoff reduction. The biological measures (forestland and grassland) also obviously affected runoff, reducing it by 877.7 × 10^3 m^3 (and accounting for 61.04% of total runoff reduction). Engineering measures (terraces and dam land) reduced runoff by 767.4 × 10^3 m^3, accounting for 53.38% of total runoff reduction. Thus, the water reduction benefit of biological measures was greater than that of the engineering measures, and among all water conservation measures, the water reducing efficiency of forestland was the highest. Other studies also have found that large-scale changes in forest area (exceeding 20% of the watershed area) have a significant impact on runoff regardless of watershed size (Brown et al. 2005; Sun et al. 2006).

Compared with the baseline period, the SWC measures reduced annual sediment yield by 84.94 × 10^3 t, accounting for 121.75% of the total sediment yield reduction. Among the conservation measures, engineering measures (terraces and dam land) had significant effects, reducing sediment yield by 717.5 × 10^3 t (102.84% of total sediment yield reduction). In contrast, biological measures (forestland and grassland) reduced the sediment yield by 131.9 × 10^3 t, accounting for 18.90% of sediment yield reduction. Obviously, the sediment reduction benefit of engineering measures is greater than that of the biological measures, and among all SWC measures, the sediment yield reducing efficiency of damming is the highest. As noted in the previous section, the World Bank loan project implemented in the Yanwachuan watershed resulted in the construction of six new warping dams before and shortly after 1996, which significantly reduced sediment yield from the watershed.

The function of biological measures in delivering water and soil conservation benefits is sustainable, so the implementation of biological measures should be strengthened for the long-term benefit of SWC. The designed service life of engineering measures is approximately 20 years. Taking the warping dams in the Yanwachuan watershed as an example, the new dams constructed before and soon after 1996 have experienced reduced retention capacity for sediment due to filling, disrepair and other reasons since 2010. The timing and non-sustainability of engineering measures in delivering water and soil conservation benefits may be the reason for the sustained growth in the annual sediment yield after 2008.

3.3 Impacts of precipitation changes and SWC measures on the runoff-sediment yield relationship

The sediment yield per unit of runoff (i.e., the ratio of sediment yield to runoff C_{RS}) can be used to characterize the runoff-sediment yield relationship (Zheng et al. 2007). Trend analysis showed that C_{RS} exhibited a significant decreasing trend ($p<0.001$), with a 69.9% reduction from the baseline period (C_{RS} = 0.088 t/m^3) to the change period (C_{RS} = 0.026 t/m^3), indicating that great changes have occurred in the runoff-sediment yield relationship. Pearson correlation analysis of C_{RS} with annual precipitation and with annual SWC measures area showed that the correlation coefficient between C_{RS} and annual precipitation was 0.204, which was not significant at $p<0.01$. Thus, precipitation had little effect on changes in water and sediment in the watershed. However, the correlation coefficient between C_{RS} and annual areas of SWC measures was -0.647 ($p < 0.01$), indicating that SWC measures had a significant impact on changes in water and sediment in the watershed and reduced the sediment yield per unit of runoff. During the period 1981–1996, the average runoff depth was 25.9 mm, and the mean sediment transport modulus was 2790 t/km^2. Compared with the baseline period, SWC measures reduced annual runoff by 6.1 mm of and sediment yield by 2863 t/km^2, a decrease of 23.6% and 102.6%, respectively, indicating that in the Yanwachuan watershed the sediment yield reducing efficiency of SWC measures is far greater than the water reducing efficiency. In our research, we analyzed the effects of precipitation and water conservation measures on runoff and sediment yield without considering the evapotranspiration increase caused by temperature rise; thus our analysis may overestimate the relative contribution of SWC measures on water and sediment yield variations.

4 Conclusions

In this study, the effects of precipitation change and soil and water conservation measures on runoff and sediment yield were analyzed using hydrologic data and implementation data on SWC measures during 1981–2012 in the Yanwachuan watershed. The trend analysis showed that there was no significant change in annual precipitation and annual runoff from 1981 to 2012, but the annual sediment yield showed a decreasing trend. The mutation test and double mass curve method both detected 1997 as the year when a significant abrupt change occurred in annual runoff and sediment yield. The contributions of SWC measures to the annual runoff and sediment yield reduction were 137.9% and 135%, respectively. Therefore, SWC measures were the main factor for the reduction of annual runoff and annual sediment yield in Yanwachuan basin. Among the SWC measures, biological measures decreased 61.04% of total runoff reduction, while engineering measures reduce sediment yield significantly (accounting for 102.84% of total sediment yield reduction).

The results showed that soil erosion control in the Loess Plateau had already demonstrated the advantages in reducing flood volumes and sediment yield on the regional scale. The implementation of SWC measures was the main reason for reductions in the annual flow and sediment yield in Yanwachuan watershed. Accordingly, in the context of global climate change, developing a reasonable land use scenario for utilizing the water and soil resources, and implementing the ecological restoration programs were the basic approaches for the adaptive watershed management strategies. Moreover, it was important to ensure a reasonable allocation proportion between biological measures and engineering measures and take advantages of various SWC measures. The results of this study can provide useful information for water resources planning and management as well as soil and water conservation in the Loess Plateau region of China.

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