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Statistical Assessment of the Impact of Conservation Measures on Streamflow Responses in a Watershed of the Loess Plateau, China

Lin Dou · Mingbin Huang · Yang Hong

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Abstract The objective of this study was to examine the trends of changes in streamflow in a watershed of the Loess Plateau, where a series of soil conservation measures were implemented since the late 1950s. Both parametric and non-parametric Mann–Kendall test were used to identify the trends in hydrologic variables over the last 50 years, and it showed significant downward trends in annual runoff, surface runoff and baseflow. The Pettitt's test was used to detect the change points of runoff, which occurred in 1973, and the whole 50-year records could be divided into contrast (from 1957 to 1973) and treated (from 1974 to 2006) periods. It was observed that the average annual runoff during treated period reduced by 60%, surface runoff and baseflow reduced by 65% and 55%, respectively in comparing with the contrast period. But the proportion of baseflow to total runoff showed a significant increasing from 0.57 to 0.63. Seasonal runoff also showed decreased trend with the highest reduction occurring in summer and lowest in winter. Annual precipitation in whole period showed no significant trend, so the changes in hydrologic variables were induced by conservation measures. Comparison of the flow duration curves for the

L. Dou · M. Huang
The State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau,
Institute of Soil and Water Conservation, CAS&MWR, Yangling,
Shaanxi Province 712100, China

L. Dou
Graduate University of Chinese Academy of Science, Beijing 100049, China

M. Huang (✉)
Northwest A&F University, Yangling, Shaanxi Province 712100, China
e-mail: hmingbin@yahoo.com

Y. Hong
University of Oklahoma, Norman, OK, USA

Y. Hong
Goddard Earth Science Technology Center at NASA GSFC, Greenbelt, MD, USA

two periods showed that reductions in high and low flows varied greatly. Results showed that conservation measures have resulted obvious changes in the hydrologic variables in a watershed of Loess Plateau.

Keywords Soil conversation · Streamflow · Trend analysis · Mann–Kendall · Regression method · Pettitt's test

1 Introduction

The Loess Plateau in the middle reaches of the Yellow River of China is the most erosive area in the world (Chen and Luk 1989). The average annual erosion rate is about 4000 t km^{-2} in gully region, and about 1000 t km^{-2} in hilly region of Loess Plateau (Ran et al. 2002). Severe soil erosion not only aggravates the fragile ecological environment, but also produces large amounts of sediment which gets deposited on the lower reaches of Yellow River, raising the riverbed, and threatening the security of the region (Tang et al. 1989). Since 1950s a great number of soil conservation measures e.g., construction of terraces and dams, tree plantation, and establishing of pastureland have been implemented to reduce soil erosion and increase rainfall use efficiency in the Loess Plateau region. These measures are very successful and reduced sediment by 3.0×10^8 t $year^{-1}$ from the Loess Plateau to the Yellow River from 1970 to 1996 (Liu et al. 2001; Wang et al. 2001; Ran et al. 2002). While the implementation of conservation measures reduced soil erosion, they have also resulted in reduction of flood peak discharges and volumes. A number of studies have showed that these measures reduced the annual total surface runoff by 1.0×10^8 m^3 $year^{-1}$ from the Loess Plateau to the Yellow River (Jing and Zheng 2004; Xu et al. 2003). However, it is not clear whether the intercepted surface runoff by the conservation measures can be transferred into baseflow and increases the streamflow to the Yellow River in dry seasons of winter and spring.

The impact of conservation measures on streamflow is generally believed to delay and reduce surface runoff (Nagasaka and Nakamura 1999; Vorosmarty et al. 2000; DeFries and Eshleman 2004; Saghafian et al. 2008). But the impact of conservation measures on baseflow had different results. Liu (2004) studied the effect of forest cover in relation to total runoff, surface runoff, and baseflow from thirteen different watersheds whose area varied from 4.37 to 25,167 km^2 with different forest covers in submontane catchments of the Loess Plateau, and found that the total runoff and surface runoff decreased, while baseflow increased with the increasing forest cover. Huang and Zhang (2004) analyzed the impact of conservation measures on the different components of runoff using precipitation and streamflow data from 1957 to 1989 in Jialuhe River watershed, a tributary of the Yellow River, with a drainage area of 1,117 km^2. It was found that conservation measures resulted in a decrease in surface runoff and base flow rates by 1.30 and 0.48 mm $year^{-1}$, respectively. At the same time the results showed the ratio of annual baseflow to total runoff increased from 0.53 to 0.61 during the contrast (1957–1966) and treated (1967–1989) periods. Furthermore, there were conflicting results on the impact of conservation measures on baseflow in other countries. Smith and Scott (1992) studied the effect of afforestation on low flows in various regions of South Africa, and found that the dry season flow was lower from forested watersheds than from natural grassland. However, Bonell and Balek (1993) and Sandström (1995) suggested an increased trend in baseflow following afforestation in some semiarid and humid regions. Therefore, it is very important to understand streamflow responses, including peak discharge, total runoff, surface runoff, and baseflow, to the conservation measures in a watershed of the Loess Plateau at different time scales (daily, seasonal, and annual scales).

The objective of this study was to statistically assess the impact of conservation measures on streamflow responses in a moderate-sized watershed in the Loess Plateau of China under a semi-arid climatic condition. More specifically, it attempts to reveal the changing trend of total runoff, surface runoff, baseflow, and baseflow index (BFI, the ratio of baseflow to total runoff) with the increasing implementation of conservation measures. The findings could be useful to understand and evaluate the soil conservation measures which have been implemented, and guide the future measures in the region.

2 Methodology

2.1 Study Area and Data

The Lu River, which is located in the Loess Plateau of China, is a tributary of the Wuding River and a sub-tributary of the Yellow River, with a drainage area of 2,415 km^2 (Fig. 1). The climate is semi-arid, with an average annual precipitation of 377 mm, of which 72% falls in the period of June to September (Fig. 2).

This watershed was selected for the study as it experienced mass land use changes caused by soil conservation practices. The treated area rose continuously since 1970, especially after 1982 when the whole Wuding River basin was chosen as one of the key controlling regions of China (Fig. 3). The type and proportional allocation of the soil conservation practices implemented in the watershed are presented in Table 1. It indicates that afforestation was the main conservation measure followed by pasture replanting.

Streamflow data was acquired using a velocity-area method from automatic measurements using a current meter (LS68-2) and water depth at a natural cross-section near the outlet of the watershed (Fig. 1). Daily precipitation was measured at seven rain gauge stations and their locations are presented in Fig. 1. Spatially averaged precipitation data were used in the analysis. The study period is chosen from 1957 to 2006.

An automated base flow separation technique using a digital filter was used to separate the daily total runoff into surface runoff and base flow (Arnold and Allen 1999). The recursive digital filter technique is described by Nathan and McMahon (1990).

2.2 Trend Test

Both parametric and non-parametric methods were used to test the trends in precipitation and runoff. The analyses focused on annual runoff, surface runoff, base flow, seasonal runoff and daily flow. The total runoff was divided into four seasons for detecting trends in seasonal runoff: spring (March to May), summer (June to August), autumn (September to November) and winter (December to

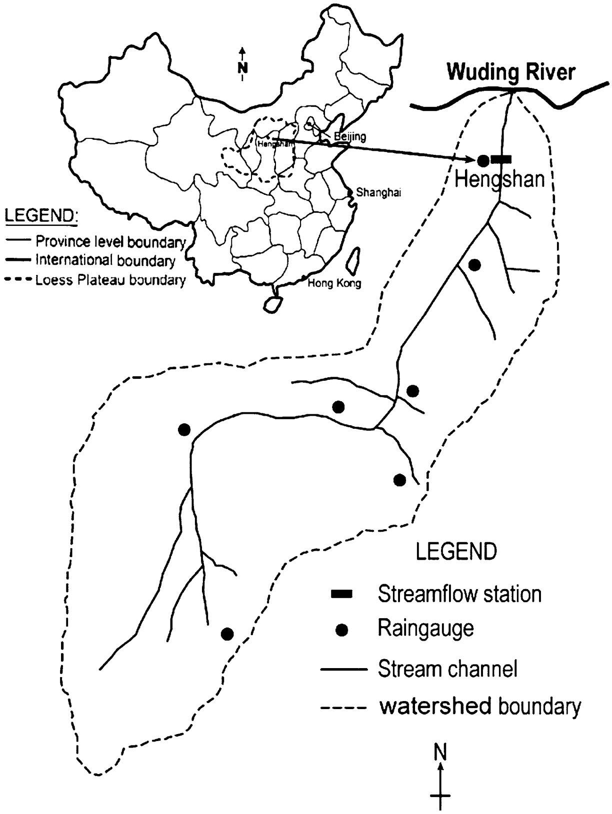


Fig. 1 Location map of study area with the hydrology and meteorology stations

February). We can find that the trend and variability in total runoff are associated with precipitation variability, especially in the first 10 years (Fig. 4). As there were no other obvious sources of non-stationary (e.g. urbanization or reservoir construction) factors affecting the trend, it was assumed that the most likely sources would be the impact of soil conservation practices and precipitation.

The time series of all the hydrologic variables were analyzed using the Mann–Kendall trend test. Mann (1945) originally used this test and Kendall (1975) subsequently derived the test statistic distribution. Most of the previous trend analyses of hydrologic data have been performed using it (Hirsch and Slack 1984; Gan 1998). This hypothesis test is a non-parametric, rank-based method for evaluating the presence of trends in time-series data. The data are ranked according to time and then each data point is successively treated as a reference data point and is compared to all data points that follow in time. Compared with parametric statistical tests, non-parametric tests are thought to be more suitable for non-normally distributed data which are frequently encountered in hydro-meteorological time series. This is the main reason for using this test.

The Mann–Kendall test statistic is given by

$$S = \sum_{\mathrm{i}=1}^{n-1} \sum_{j=\mathrm{i}+1}^{n} \operatorname{sgn}\left(x_{\mathrm{j}} - x_{\mathrm{i}}\right) \tag{1}$$

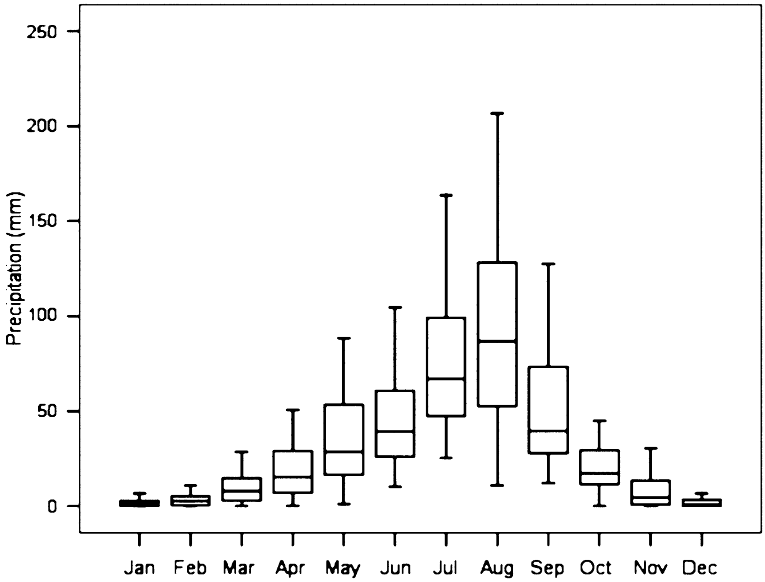


Fig. 2 Distribution of monthly precipitation for the study area during the period 1957–2006 (*whiskers* indicate the 5th and 95th; *box boundaries* indicate the 25th and 75th; the *line within each box* indicates the median value)

where x_i and x_j are the sequential data values, n is the data set record length, and

$$\operatorname{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \quad if & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{2}$$

The Mann–Kendall test has two parameters that are of importance to the trend detection. These parameters are the significance level that indicates the trend's strength, and the slope magnitude estimate which indicates the direction as well

Fig. 3 Time series of annual treated area (percent) of total area in the experimental watershed

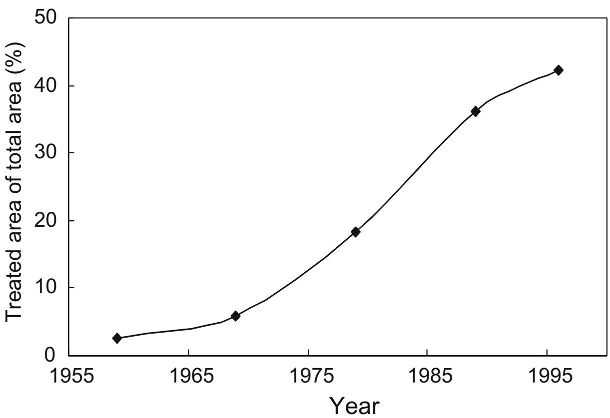


Table 1 Areas occupied by the different soil conservation measures

Year	Terrace		Afforestation		Pasture		Dams	
	km^2	RA[a](%)	km^2	RA[a](%)	km^2	RA[a] (%)	km^2	RA[a](%)
1959	4.91	8	36.13	59	20.39	33	0.11	0
1969	22.79	16	100.13	71	15.76	11	3.48	2
1979	47.19	11	333.93	76	47.76	11	10.71	2
1989	77.9	9	709.77	81	72.3	8	14.44	2
1996	99.61	10	840.38	82	66.36	6	15.45	2

[a]RA means the ratio of the area covered by single conservation measure to the total area covered by all measures (%)

as the magnitude of the trend. For independent, identically distributed random variables with no tied data values, we have

$$E(S) = 0 \tag{3}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{4}$$

When some data values are tied, the correction to Var(S) is

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{5}$$

Where t_i denotes the number of ties of extent i. For n larger than 10, the test statistic

$$Z_S = \begin{cases} \frac{S-1}{[\mathrm{var}(S)]^{0.5}} & S > 0 \\ 0 & for\ S = 0 \\ \frac{S+1}{[\mathrm{var}(S)]^{0.5}} & S < 0 \end{cases} \tag{6}$$

Z_S follows the standard normal distribution (Kendall 1975).

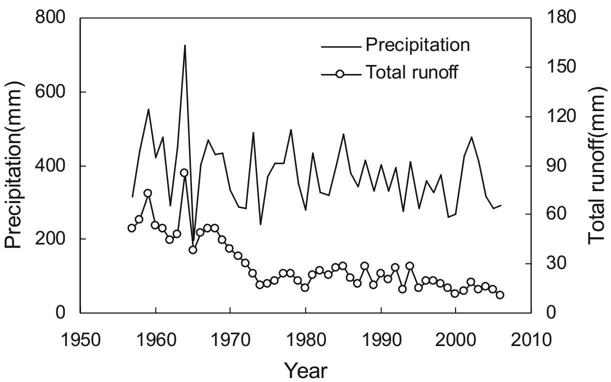


Fig. 4 Time-series of annual total runoff and precipitation in the experimental watershed

The magnitude of trend slopes can be also calculated (Sen 1968). Sen's estimate for slope is associated with the Mann–Kendall test as follows:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall j > i \tag{7}$$

A positive value of β indicates an upward trend, whereas a negative value represents a downward trend.

The concern for the Mann–Kendall approach is that the existence of positive serial correlation in time series data increases the probability that a trend is detected when it does not exist (von Storch 1995; Kulkarni and von Storch 1995; Yue et al. 2002; Yue and Wang 2004). In order to eliminate the overestimation, von Storch (1995) and Kulkarni and von Storch (1995) proposed applying the Mann–Kendall trend test to the pre-whitened series XP_t, when there is a time series with autocorrelation coefficients larger than 0.1:

$$\text{XP}_t = X_{t+1} - rX_t \tag{8}$$

Where XP_t is the pre-whitened series value for time interval t, X_t is the original time-series value for time interval t and r is the estimated serial coefficient.

2.3 Change-Point Analysis

The non-parametric approach by Pettitt (1979) was used in this study. This approach detects one unknown change point by considering a sequence of random variables X_1, X_2, ..., X_T which may have a change-point at N if X_t for $t = 1,2,..., N$ have a common distribution function $F_1(x)$ and X_t for $t = N+ 1,..., T$ have a common distribution function $F_2(x)$, and $F_1(x) \neq F_2(x)$ (Pettitt 1979).

The null hypothesis H_0: no change or $N = T$ is tested against the alternative hypothesis H_a: change or $1 < N < T$ using the non-parametric statistic

$$K_t = \text{Max}_{1 \le t \le T} \left| U_{t,T} \right| \tag{9}$$

$$U_{t,T} = U_{t-1,T} + \sum_{j=1}^{T} \text{sgn}\left(X_t - X_j\right), \ \text{for } t = 2, ..., T \tag{10}$$

where

$$\text{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 \;\; if & \theta = 0 \\ -1 & \theta < 0 \end{cases} \tag{11}$$

and

$$p = 2\exp\left\{-6K_T^2 / T^3 + T^2\right\} \tag{12}$$

When p is smaller than the specific significance level, e.g. 0.05 in this study, the null hypothesis is rejected. The time t when the K_t occurs is the change point time.

2.4 Flow Duration Curve

The flow-duration curve (FDC) is a cumulative curve that shows the percent of time specified discharges were equaled or exceeded during a given period (Searcy 1959). It combines in one curve the flow characteristics of a stream throughout the range of discharge in one curve, and it represents the relationship between the magnitude and frequency of streamflow. The FDCs can be constructed from daily, monthly or some other time intervals of the streamflow data and provide a graphical view of the overall historical variability. Each value of discharge (Q) has a corresponding exceedance probability p, and the flow-duration curve is a plot of Q_p, the pth percentile of streamflow versus the exceedance probability p, where p is defined by:

$$p = 1 - p\left\{Q_{\mathrm{p}} \leq q\right\} \tag{13}$$

3 Results

3.1 Precipitation Analysis

It is well known that precipitation is the dominant factor affecting the runoff, and any trends in precipitation will affect the trends in runoff (Gan 2000; Xu 2000). For the Lu River experimental watershed, the trends in precipitation were tested using the Mann–Kendall and the regression methods, both tests showed that the downward trends in precipitation were not significant at the level of 0.05 (Table 2). The rate of change estimated by the Mann–Kendall method is lower than that estimated by the regression method.

The Pettitt's test was also used to detect the change in precipitation and the results are shown graphically in Fig. 5. The null hypothesis of no change in precipitation can not be rejected at the significance level of 5%. Hence the result implies that precipitation is not a significant factor on the changes of runoff.

3.2 Annual Runoff

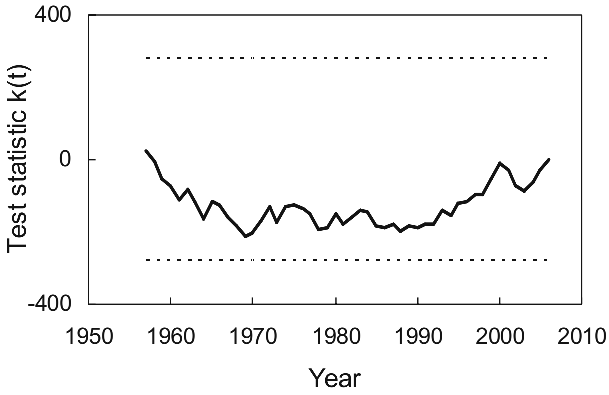
The results of the trend analysis for the runoff using the Mann–Kendall and the regression methods are shown in Table 3. Both methods indicated highly significant downward trends ($P < 0.05$) on these variables. Based on the Mann–Kendall test,

Table 2 Results of trend tests for observed precipitation variables during the period (1957–2006)

Time-series	Regression		Mann–Kendall	
	Slope (mm/year)	Significance level of 5%	Slope (mm/year)	Significance level of 5%
Annual precipitation	−1.93	NS	−1.85	NS
Spring precipitation	−0.39	NS	−0.33	NS
Summer precipitation	−1.01	NS	−1.00	NS
Autumn precipitation	−0.90	NS	−0.69	NS
Winter precipitation	0.04	NS	0.07	NS

NS not significant at the level of 0.05

Fig. 5 Pettitt's test for detecting a change in annual precipitation. The *dotted lines* represent the significance levels of 5%



the slopes of the trends in total runoff, surface runoff and base flow were found to be −0.82, −0.36 and −0.45 mm per year respectively during the whole period.

The Pettitt's test was used to detect the changes of annual runoff (Fig. 6). A change point was detected in 1973 with a significance level of 5% for the annual total runoff. K_T was 547 and p was much less than 0.0001. The change points of surface runoff and base flow were also in 1973, respectively.

Based on the Pettitt's test, daily streamflow records could be divided into contrast period from 1957 to 1973, with no significant change in annual streamflow, and treated period from 1974 to 2006, with significant change in annual streamflow. Data from the contrast period was used as the basis for comparison with the treated period. Compared with the contrast period, the average annual runoff was reduced by 60%. The reduction in annual total runoff can be attributed to decreased surface runoff and base flow. The surface runoff reduced by 65% and rate of the base flow was 55%. The trend of BFI (base flow index) was also tested, which demonstrated significant change in the 50 years using both methods, the annual average BFI increased from 0.57 to 0.63 from contrast to treated periods.

Table 3 Results of trend analysis for runoff variables in the period (1957–2006)

Time-series	Regression		Mann–Kendall	
	Slope (mm/year)	Significance level (F)	Slope (mm/year)	Significance level (F)
Annual				
Total runoff	−0.92	< 0.05	−0.82	< 0.05
Surface runoff	−0.45	< 0.05	−0.36	< 0.05
Baseflow	−0.47	< 0.05	−0.45	< 0.05
Baseflow index	0.003	< 0.05	0.003	< 0.05
Seasonal total runoff				
Spring	−0.23	< 0.05	−0.21	< 0.05
Summer	−0.31	< 0.05	−0.26	< 0.05
Autumn	−0.23	< 0.05	−0.20	< 0.05
Winter	−0.16	< 0.05	−0.14	< 0.05

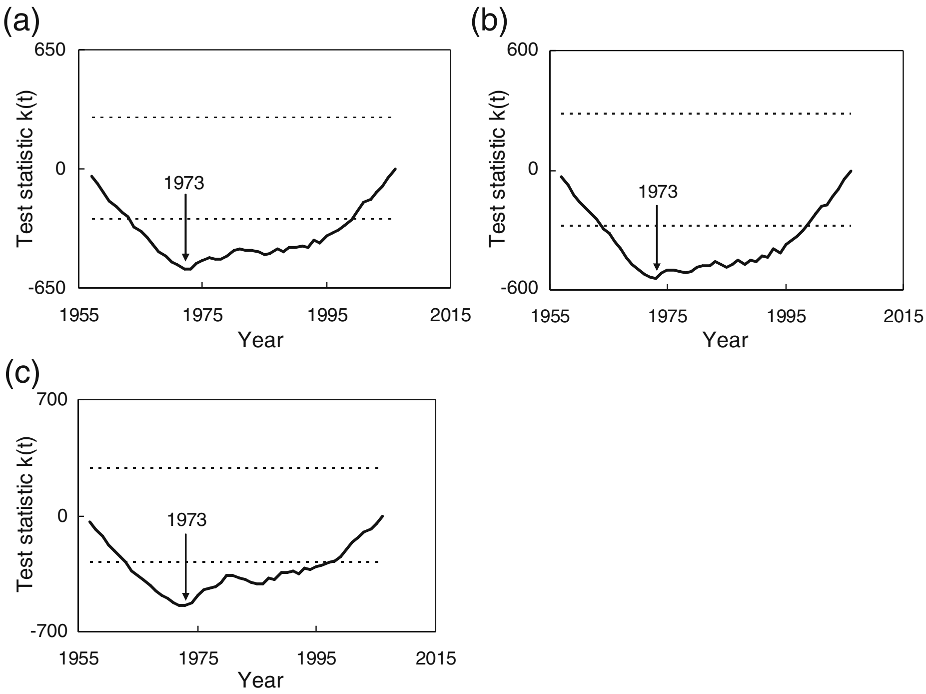


Fig. 6 Pettitt's test for detecting a change in the mean of **a** annual runoff, **b** surface runoff and **c** baseflow. The *dotted lines* represent the significance level of 5%

3.3 Seasonal Runoff

It is clear that all seasonal runoffs significantly decreased over the whole time, and based on the Mann–Kendall test, the trends were −0.21, −0.26, −0.20, and −0.14 mm per year for spring, summer, autumn, and winter, respectively (Table 3). The summer runoff shows the strongest decreasing trend and the winter runoff is the weakest. The average monthly runoff was compared between contrast and treated periods. The absolute and relative reductions in runoff were highest in August and lowest in June (Fig. 7).

3.4 Daily Flow

Figure 8 shows the daily FDC for the whole period of records. The slope of the FDC is gentle for flows between Q_5 to Q_{95}, indicating little relative variability in daily stream flow. To further examine daily stream flow variability, we define high flows which are flows exceeding 5%, i.e., Q_5, and low flows as being 95%, i.e., Q_{95}. The ratio of these flows to median streamflow (Q_{50}) is a measure of stream flow variability; these ratios are listed in Table 4. The high flow index (Q_5/Q_{50}) is 3.18 and the low flow index (Q_{95}/Q_{50}) is 0.31.

Figure 9 shows the daily flow duration curve for the two periods. The characteristic ratios are shown in Table 4. The reduction in flows was relatively constant, except for

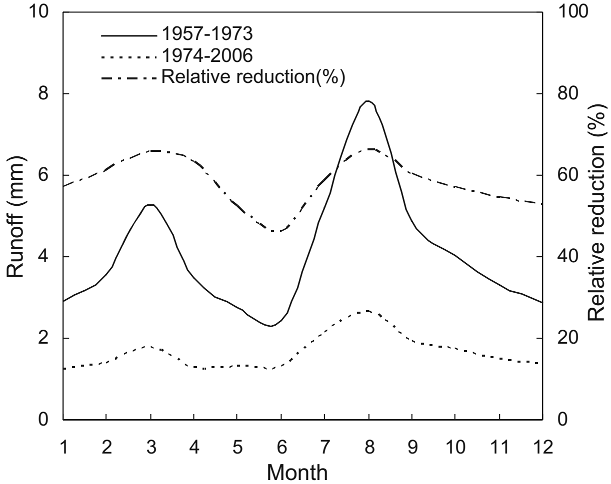


Fig. 7 Average monthly runoff between the contrast period of 1957–1973 and treated period of 1974–2006

the extremely high and low flows. The results indicate that there was approximately a 54% reduction in most flows, and the average reduction in high and low flows was 65% during the treated period. Median daily flow reduced from 2.66 to 1.21 m^3/s, while the coefficient of variation decreased from 1.31 to 1.19. The high flow index (Q_5/Q_{50}) in the treated period increased by 9%, and the low flow index (Q_{95}/Q_{50}) showed an 11% reduction.

4 Discussions

This paper has attempted to estimate the changes in stream flow regime of a selected watershed in the Loess Plateau where a series of soil conservation practices was carried out. The study area is the Lu River, a tributary of the Wuding River and a sub-tributary of the Yellow River, with a drainage area of 2,415 km^2. Data of areas occupied by the different soil conservation measures were collected to confirm the

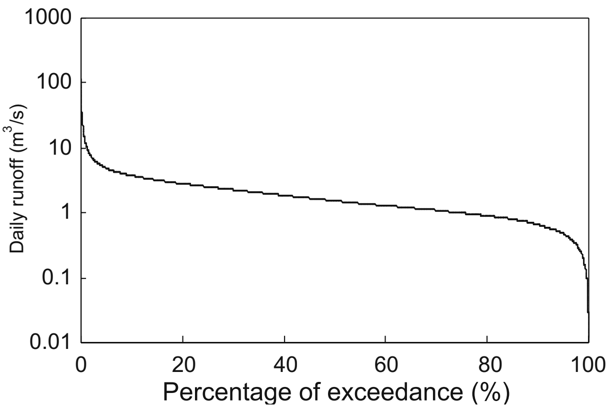


Fig. 8 Daily flow duration curve for the whole period of records

Table 4 Characteristics of daily flow duration curve

Index	Total period (1957–2006)	Contrast (1957–1973)	Treated (1974–2006)
Q_{50} (m^3/s)	1.53	2.66	1.21
Q_5/Q_{50}	3.18	2.56	2.80
Q_{95}/Q_{50}	0.31	0.37	0.33
C_V	1.44	1.31	1.19

land use changes, precipitation and hydrological data were analyzed to detect the changing trend.

First, precipitation was analyzed for the period because it is the source of runoff and the main factor impacting the runoff. The results showed that the changes in precipitation were not significant at the significance level of 5%. Because climate and land use changes were the dominating impact factors in this watershed, and there was no other obvious non-stationary factor, so, all the changes in stream flow were considered as being induced by large-scaled conservation measures.

It is obvious that the stream flow characteristics of the Lu River watershed were modified dramatically in the last 50 years. Significant change was detected at a significance level of 5% in 1973 for the annual runoff, surface runoff and base flow. Since the change points, these three flow values showed decreasing trend. The changes in runoff were relevant to the land-use changes in the watershed. The controlling area of soil conservation practices rose continuously since 1970s (Fig. 3), the change point in 1973 was synchronous with it. Thus, the whole period (1957–2006) could be divided into two stages: contrast period (1957–1973) and treated period (1974–2006). The area of conservation practices increased almost four times while the average annual total runoff reduced by 60%.

The baseflow volume was reduced, but the proportion of baseflow to total runoff showed a significant increase from 0.57 to 0.63. The seasonal runoffs also showed decreased trends, summer runoff showed the highest reduction and winter was the lowest. Runoff in this watershed displayed the seasonal characteristics because of seasonality in precipitation. This region is characterized as semi-arid continental

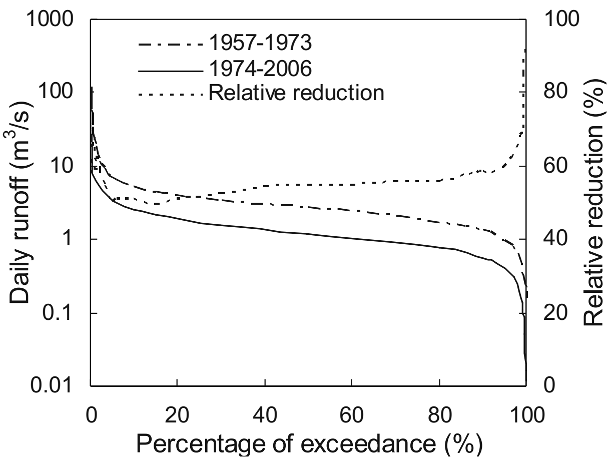


Fig. 9 Comparison of daily flow duration curve between the contrast of 1957–1973 and treated of 1974–2006 periods

monsoon climate in North Temperate Zone, where high-intensity rainfall events are more likely to occur in the summer season, so most streamflow focuses on the summer and it often presents in short duration heavy rainfall. One important function of the soil conservation practices is to reduce the peak flow that is the reason why summer runoff showed the high decrease. The average monthly flow between baseline and treated periods showed the highest reduction which occurred in the month of August.

The flow duration curve for the whole period demonstrated little variability for flows between 5% and 95% exceedance level. Comparing the daily flow of treated period with that of the baseline period, the high flow and low flow decreased more. Assuming the soil conservation measures especially the terraces and dams can intercept surface flow, the total runoff can be considered as more stable.

As for the conclusion of that the streamflow reduced under the influence of soil conservation practices, it is consistent with other research results (Potter 1991; Huang and Zhang 2004). The dams and terraces can effectively control the surface flow and impact the flow duration (Zhan and Yu 1994). Though the area occupied by these engineering measures was limited, their controlling area was dramatically large. Another function of the soil conservation practices was that it intercepted rainfall and transferred rainfall into baseflow (Xu and Singh 1998). But in studied watershed, the baseflow volume reduced, although the baseflow index showed a significant increment. The main reason was that the soil and water conservation practices increased the forest and pasture coverage in watershed, so the growth of forest and pasture consumed more soil storage water than natural grasses and crops. The soil water transferred from rainfall by soil and water conservation practices could not recharge groundwater for increasing baseflow. Huang and Gallichand (2006) studied the effect of cropland converted to apple trees on groundwater recharge in the Loess Plateau, and their results showed that the groundwater recharge amount decreased 50% during the study period of 40 years.

The results of this research may be useful to the future soil conservation planning, and the hydrological responses could be considered in the subsequent control, because of the water resources shortage, if the conservation measures decrease the steam flow excessively, the downstream water demand will be in danger. As for the reasonable degree of conservation control, it needs further researches.

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