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Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China

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Abstract:

Catchments in the Loess Plateau have been under the influence of human activities for centuries. In the last four decades, soil conservation measures have accelerated and intensified. These measures were designed to reduce soil erosion, improve agricultural productivity, and enhance environmental quality. It is important to evaluate the effects of these measures on hydrology in order to develop sustainable catchment management plans in the region. This study evaluated changes in stream flow data for four selected catchments in the Loess Plateau following large-scale soil conservation measures. The non-parametric Mann–Kendall test was used to identify trends in annual stream flow and the results showed significant downward trends in three of the four catchments. The Pettitt test indicated that a change point occurred in 1978 in these three catchments. Annual precipitation in all the catchments showed no significant trend during the period of record. Comparison of daily flow duration curves for two 20-year periods (1957–1978) and (1979–2003) showed significant changes in stream flow regime. Reduction in most percentile flows varied between 20 and 45%, and the reduction in low flows was greatest. Overall, the reductions in daily flow were increasing with time, with significant changes occurring in the 1990s. However, it is not clear whether these catchments have seen the full effects of the soil conservation measures, so the results of this study might underestimate the final impact of soil conservation on stream flow regime. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS soil conservation; stream flow regime; Loess Plateau; flow duration curves; stream flow trend; change-point analysis

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INTRODUCTION

The catchments in the Loess Plateau (623 586 km^2) of China have been known to contribute significantly to the total sediment yield from the Yellow River basin (752 444 km^2). The average annual erosion rate (2480 t km^{-2}) for the Yellow River basin is the highest of any major river system worldwide (Ludwig and Probst, 1998; Shi and Shao, 2000). This is primarily a result of the severe soil erosion from the Loess Plateau; rates ranging from 20 000 to 30 000 t km^{-2} year^{-1} are commonly reported (e.g. Xu *et al.*, 2004), though extremely high rates (59 700 t km^{-2} year^{-1}) have also been documented (Shi and Shao, 2000). Since the 1950s, a number of conservation measures have been implemented in the catchments of the Loess Plateau to control soil erosion and maintain agricultural productivity. These conservation measures include building terraces, sediment trapping dams, and changing land cover by replanting trees and improving pastures. Although these measures have reduced soil erosion, they also result in noticeable changes in the stream flow regime. Establishment of terraces on hill slopes reduces surface runoff and enhances infiltration and actual evapotranspiration. The methods available for estimating runoff reduction due to terraces are empirical (Mu *et al.*, 2001). Sediment-trapping dams reduce surface runoff, and hence are hydrologically similar to reservoirs when their storage capacity is not fully filled with sediment. However, their impact on runoff is similar to terraces once they are filled sediment. As they are not sealed, sediment-trapping dams are likely to increase base flow. The effects of sediment trapping dams on stream flow have traditionally been determined using engineering methods by considering storage capacity (Zhan and Yu, 1994; Mu *et al.*, 2001). For example, Xu and Niu (2000) investigated the impact of engineering measures (mainly dams) on mean annual stream flow, and Mu (2002) estimated their impact on annual stream flow variability and floods using time-series analysis. Afforestation will lead to greater evapotranspiration and reduced water yield (Zhang *et al.*, 2001) and it can also modify stream flow regime (Brown *et al.*, 2005). The hydrologic effect of afforestation has been investigated by Liu and Zhong (1978) and Huang and Zhang (2004) for some catchments in the region. However, it is not clear whether these results can be generalized to the region.

Given the complex nature of the conservation measures in the Loess Plateau, it is difficult to isolate the effects of individual treatments on stream flow. Although the

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areas of conservation measures are known, the exact locations are not; this prevents the use of detailed spatially distributed models. However, by analysing patterns in the precipitation–flow relationships, and knowing the relative area (but not exact locations) and timing of soil conservation measures, it is possible to examine the combined effects of soil conservation measures on catchment stream flow.

The objective of this study was to examine changes in stream flow regime due to implementation of conservation measures in four major catchments in the Loess Plateau. Such information can help catchment managers evaluate the effects of the soil conservation measures implemented in the last four decades, thus guiding future measures in the region. The study used daily flow duration curves (FDCs) to represent daily stream flow regime and assesses changes in FDCs in these catchments between the 1950s and 2003.

MATERIALS AND METHODS

Study areas and data

The middle reaches of the Yellow River basin are characterized as semi-arid continental monsoon climate in the North Temperate Zone. In order to detect a significant change in stream flow, catchments with a large percentage change in land use were required. Four catchments in this region were selected in this study: the Jialu River, the Qiushui River, the Tuwei River, and the Yanhe River catchments. These catchments were selected as they represent the different hydrologic conditions in the region and have all undergone substantial land-use changes due to soil conservation measures.

The Jialu River catchment is mostly characterized by hills with loess soil except near the outlet, where deep, narrow gullies exist. The Qiushui River catchment is characterized by loess hills and bed rocks, and it is highly fragmented with gullies. In the Tuwei River catchment, the upper and middle reaches are mostly hills of sandy soil, with the lower reaches dominated by loess soil. The Yanhe River catchment is dominated by hills with loess soil and it is also highly fragmented with gullies. The locations of these catchments are shown in Figure 1 and detailed information is listed in Table I. The daily precipitation and daily runoff data were provided by the Water Resources Committee of the Yellow River. The distribution of rainfall and hydrology stations is shown in Figure 1.

Implementation of soil conservation measures

The main soil conservation measures in the Loess Plateau include afforestation, establishing pastures, and constructing terraces and sediment-trapping dams. The areas occupied by different soil conservation measures in the four catchments are listed in Table II. These data were collected through censuses and they include areas occupied by each soil conservation measure and year of establishment. In the case of sediment-trapping dams, the areas were estimated based on the design of the dams. The data were collected at each village and aggregated to the county level. The accumulated area covered by conservation measures was over 10% in the Jialu and Qiushui river catchments in the mid 1970s, and in the Tuwei and Yanhe river catchments in the early 1980s. By the end of 1996, the total areas covered by conservation measures were 41·8%, 33·4%, 35·1% and 28·5% respectively in the Jialu, Qiushui, Tuwei, Yanhe river catchments. Engineering measures (i.e. terraces and sediment dams) were significant in the Jialu River and the Qiushui River catchments, whereas vegetation controls (i.e. afforestation and pastures) were dominant in the Tuwei River and the Yanhe River catchments on an area basis. It can be seen that the major expansion in soil conservation measures took place in the decade 1979 to 1989 (see Table II).

Trend test

The non-parametric test based on the Mann–Kendall rank correlation coefficient is used in this study (Mann, 1945; Kendall, 1975); the method has been commonly used to assess the significance of trends in hydro-meteorological time-series. The main reason for using non-parametric statistical tests is that, compared with parametric statistical tests, the factors are thought to be more suitable for non-normally distributed data, which are frequently encountered in hydro-meteorological time-series.

The Mann–Kendall test statistic is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

and

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

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

The Mann–Kendall test has two parameters that are of importance to trend detection: the significance level, which indicates the trend's strength; and the slope magnitude estimate, which indicates the direction and magnitude of the trend. The null hypothesis of an upward (or downward) trend in the data cannot be rejected, if S has a mean of zero and a variance of

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

and is asymptotically normal. The normal z-test statistic is

$$z = \frac{S}{[\operatorname{Var}(S)]^{0\cdot 5}} \tag{4}$$

The statistic z can be compared for any values of i to detect whether there is a trend in the data up to i at the chosen level of significance using the z-test. The robust

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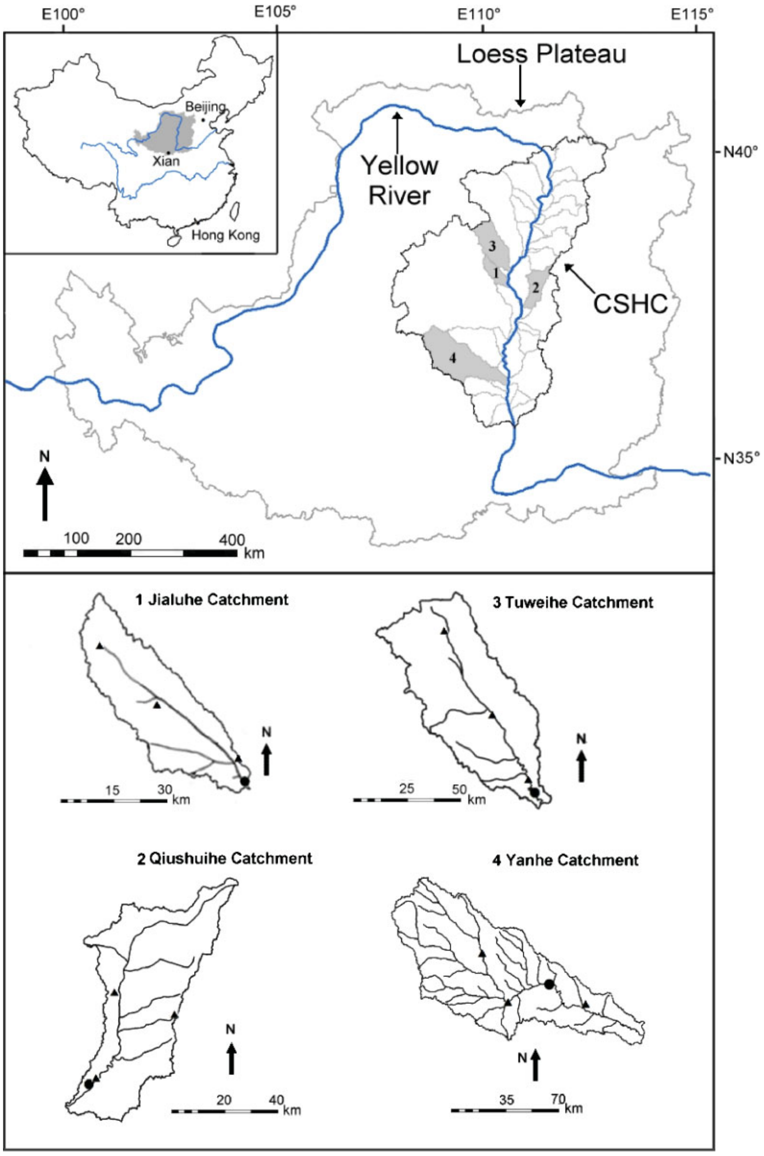

Figure 1. The main map shows the location of the four study catchments in the Coarse Sandy Hilly Catchments (CSHC - bordered by the black line) with the Loess Plateau (bordered by the grey line and shaded in the inset map of China). Detailed maps of the four catchments are shown, with circles and triangles representing the hydrology and meteorology stations respectively

Table I. Catchment characteristics and stream flow records

Catchment	Average Precipitation (mm year^{-1})	Average PET[a] (mm year^{-1})	Average Runoff (mm year^{-1})	Area (km^2)	Stream length (km)	Average slope (‰)	Runoff records
Jialu	395	2010	62	1134	93·0	6·3	1957–2003
Qiushui	509	1820	42	1989	122·0	6·4	1956–2003
Tuwei	393	1870	111	3294	139·6	3·2	1956–2003
Yanhe[b]	511	1520	29	7725	286·9	3·3	1957–2003

[a] Potential evapotranspiration (PET) was estimated using the Penman equation (Penman, 1948).

[b] There are no stream flow data for 1994 and 1995.

non-parametric estimate of the magnitude of the slope β is (Hirsch *et al.*, 1982)

$$\beta = \text{Median}\left[\frac{(x_j - x_k)}{j - k}\right] \qquad \text{for all } k < j \qquad (5)$$

A positive value of β indicates an upward trend and a negative value represents a downward trend. In addition, to confirm the results provided by the Mann–Kendall test, we also performed linear regression analysis.

The results of the trend test can be used to determine whether or not the observed time-series of hydrological variables exhibits a trend that is statistically significant from a trend that could occur by chance. However, to do this, it is necessary to test the serial correlation of the

Table II. Areas occupied by the different soil conservations measures[a]

Catchment	Year	Terrace		Dams		Afforestation		Pasture		Total area (km^2)	RPC (%)
		km^2	RA (%)	km^2	RA (%)	km^2	RA (%)	km^2	RA (%)		
Jialu (1134 km^2)	1959	4·3	26	0·8	5	9·2	55	2·3	14	16·7	1·5
	1969	27·3	36	4·1	5	41·7	56	1·7	2	74·7	6·7
	1979	67·1	36	9·7	5	97·5	53	10·2	6	184·6	16·5
	1989	104·3	25	12·9	3	293·9	69	12·8	3	423·9	37·8
	1996	141·4	30	16·3	3	295·3	63	15·5	3	468·5	41·8
Qiushui (1989 km^2)	1959	21·3	50	2·8	7	15·1	35	3·4	8	42·6	2·3
	1969	72·4	59	4·6	4	37·3	30	8·3	7	122·6	6·5
	1979	141·9	51	12·7	5	113·6	41	12·1	4	280·3	15·0
	1989	167·2	42	17·5	4	200·7	50	14·8	4	400·2	21·4
	1996	263·4	42	24·2	4	318·5	51	19·8	3	625·8	33·4
Tuwei (3294 km^2)	1959	1·0	4	0·2	1	25·4	91	1·4	5	28·0	0·9
	1969	10·8	11	1·7	2	77·1	81	6·1	6	95·7	2·9
	1979	31·3	14	7·1	3	174·7	76	16·1	7	229·2	7·0
	1989	45·5	5	11·1	1	754·5	90	28·8	3	839·9	25·8
	1996	66·5	6	15·5	1	1021·6	90	37·4	3	1140·9	35·1
Yanhe (7725 km^2)	1959	4·1	8	4·6	9	41·3	82	0·3	1	50·4	0·9
	1969	47·2	21	15·8	7	161·3	71	3·7	2	228·0	3·9
	1979	97·5	23	28·7	7	286·9	67	17·5	4	430·7	7·3
	1989	174·3	15	37·8	3	840·7	70	145·2	12	1198·1	20·3
	1996	275·6	16	41·7	2	1100·2	66	259·9	15	1677·3	28·5

[a] RA is the ratio of the area covered by single measure divided by the total area covered by all measures; RPC refers to the proportion of the total area covered by all measures in the area contributing to measurements at the gauging stations. The dam area refers to the amount of 'new' horizontal farmland that is created behind the sediment-trapping dam wall, not the contributing area to the sediment dam.

data (Jenkins and Watts, 1968). The presence of serial correlation can complicate the identification of trends, in that a positive serial correlation can increase the expected number of false positive outcomes for the Mann–Kendall test (von Storch and Navarra, 1995). One of the common approaches for removing the impact of serial correlation from the data set prior to applying the Mann–Kendall trend test is to use prewhitening (Burn and Elnur, 2002). The pre-whitening is accomplished through

$$xp_t = x_{t+1} - rx_t \tag{6}$$

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 correlation coefficient.

Change-point analysis

The non-parametric approach developed by Pettitt (1979) was used in this study. This approach detects a significant change in the mean of a time-series when the exact time of the change in unknown. The test uses a version of the Mann-Whitney statistic $U_{t,N}$, which verifies whether two samples $x_1, \ldots, x_t$ and $x_{t+1}, \ldots, x_N$ are from the same population or not. The test statistic $U_{t,N}$ is given by

$$U_{t,N} = U_{t,-1,N} + \sum_{j=1}^{N} \mathrm{sgn}(x_t - x_j) \text{ for } t = 2, \ldots, N \tag{7}$$

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The null hypothesis of Pettitt's test is the absence of a changing point. Its statistic $k(t)$ and the associated probabilities used in significance testing are given as

$$k(t) = Max_{1 \le t \ge N} |U_{t,N}| \tag{8}$$

and

$$p \cong 2\exp\{-6(K_N)^2/(N^3 + N^2)\} \tag{9}$$

Flow duration curve (FDC)

An FDC represents the relationship between the magnitude and frequency of stream flow. FDCs are constructed from stream flow data over a time interval of interest, such as daily, weekly, monthly or annually, and provide a measure of the percentage of time a given stream flow is equalled or exceeded over that interval. An FDC provides a simple, yet comprehensive, graphical view of the overall historical variability associated with stream flow and is the complement of the cumulative distribution function of daily stream flow. Each value of discharge Q has a corresponding exceedance probability p; and an FDC is simply a plot of Q_p, the pth quantile or percentile of stream flow versus exceedance probability p, where p is defined by

$$p = 1 - p\{Q_p \le q\} \tag{10}$$

The quantile Q_p is a function of the observed stream flow, and since this function depends upon observations, it is often termed the empirical quantile function (Vogel and Fennessey, 1994).

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RESULTS

Annual stream flow trend

Annual stream flow trends in the four catchments were tested using the Mann–Kendall and the regression methods; see Table III. Three of four catchments showed strong decreasing trends in annual stream flow. The Yanhe River catchment showed a weak increasing trend based on the regression analysis. The Mann–Kendall test suggests that the increasing trend for the Yanhe River catchment is not significant. For the three catchments with decreasing trend, the rate of decline in stream flow is between 0·734 and 0·38 mm year^{-1}, depending on the method used. The rate of change estimated by the Mann–Kendall method is lower than that estimated by the regression method. For the Yanhe River catchment, the rate of increase in stream flow is at most 0·26 mm year^{-1} based on the regression analysis.

The Pettitt test was also used to detect changes in annual stream flow from the catchments, and the results are shown graphically in Figure 2a–d. A change point was detected in 1978 for the Jialu, Qiushui, and Tuwei river catchments, with a significance level of 5%. However, the null hypothesis of no change in annual stream flow cannot be rejected at the 5% significance level for the Yanhe River catchment. This result is consistent with the Mann–Kendall test (Table III). Similar analyses were also carried out for annual precipitation, and no significant trends were detected (Table IV). The Pettitt test was also applied to annual precipitation for the four catchments, and the null hypothesis of no change in annual precipitation could not be rejected at the 5% significance level in any of the catchments (Figure 3).

Characteristics of flow duration curves for the whole period of record

Figure 4 shows the daily FDCs for the whole period of records for each catchment. Flows that are exceeded 50% of the time are $Q_{50} = 0{\cdot}085$ mm day^{-1}, 0·03 mm day^{-1}, 0·252 mm day^{-1}, and 0·047 mm day^{-1} for the Jialu, Qiushui, Tuwei, and Yanhe river catchments respectively. The slopes of the FDCs are gentle for flows between

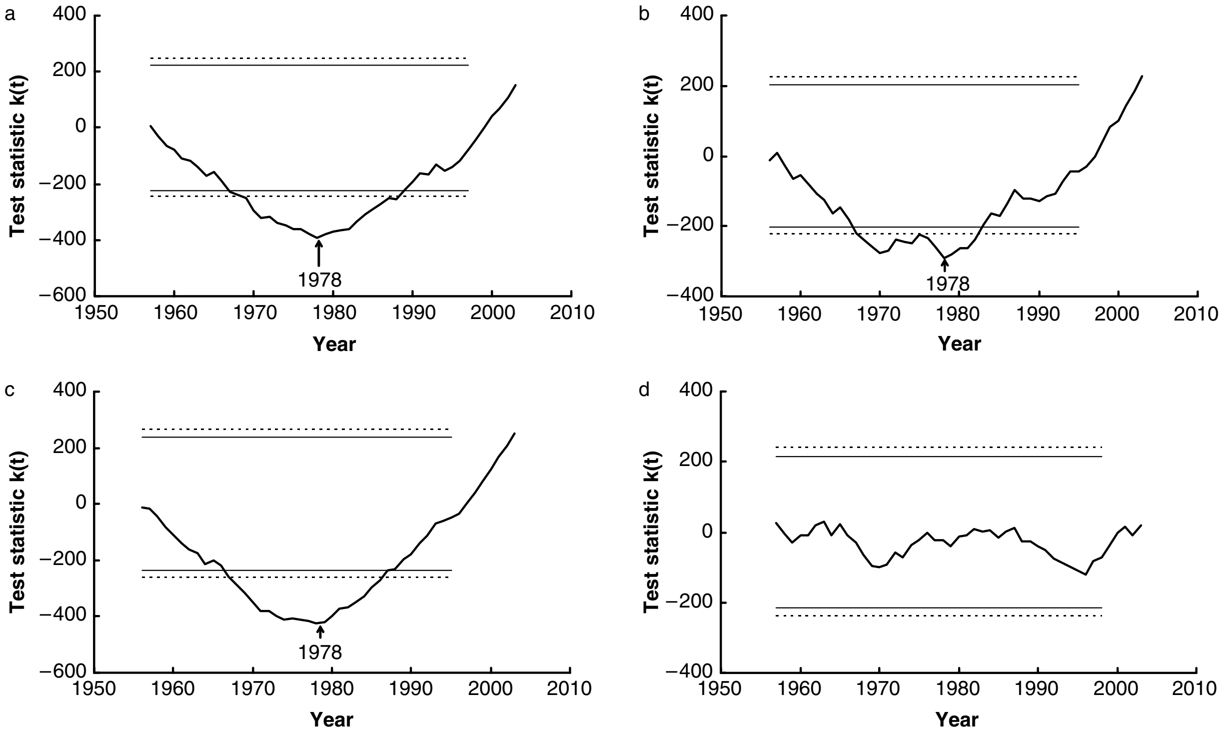

Figure 2. The Pettitt test for detecting a change in the mean of annual stream flow for the (a) Jialu, (b) Qiushui, (c) Tuwei, and (d) Yanhe catchments. Horizontal lines represent the 5% (dotted) and 10% (solid) significance levels

Table III. Results of trend analysis for annual stream flow in the selected catchments

Catchment	Regression analysis		Mann–Kendall	
	Slope (mm year^{-1})	Significance level	Slope (mm year^{-1})	Significance level[a]
Jialu	−0·734	0·01	−0·546	0·01
Qiushui	−0·629	0·01	−0·380	0·01
Tuwei	−0·723	0·01	−0·587	0·01
Yanhe	0·262	0·05	0·036	ns

[a] ns: Significance level exceeds 0.05.

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Table IV. Results of trend analysis for annual precipitation in the selected catchments

Catchment	Regression analysis		Mann–Kendall	
	Slope (mm year^{-1})	Significance level[a]	Slope (mm year^{-1})	Significance level[a]
Jialu	−0·203	ns	−0·143	ns
Qiushui	−0·173	ns	−0·096	ns
Tuwei	−0·348	ns	−0·241	ns
Yanhe	−0·059	ns	0·027	ns

[a] ns: significance level exceeds 0.05.

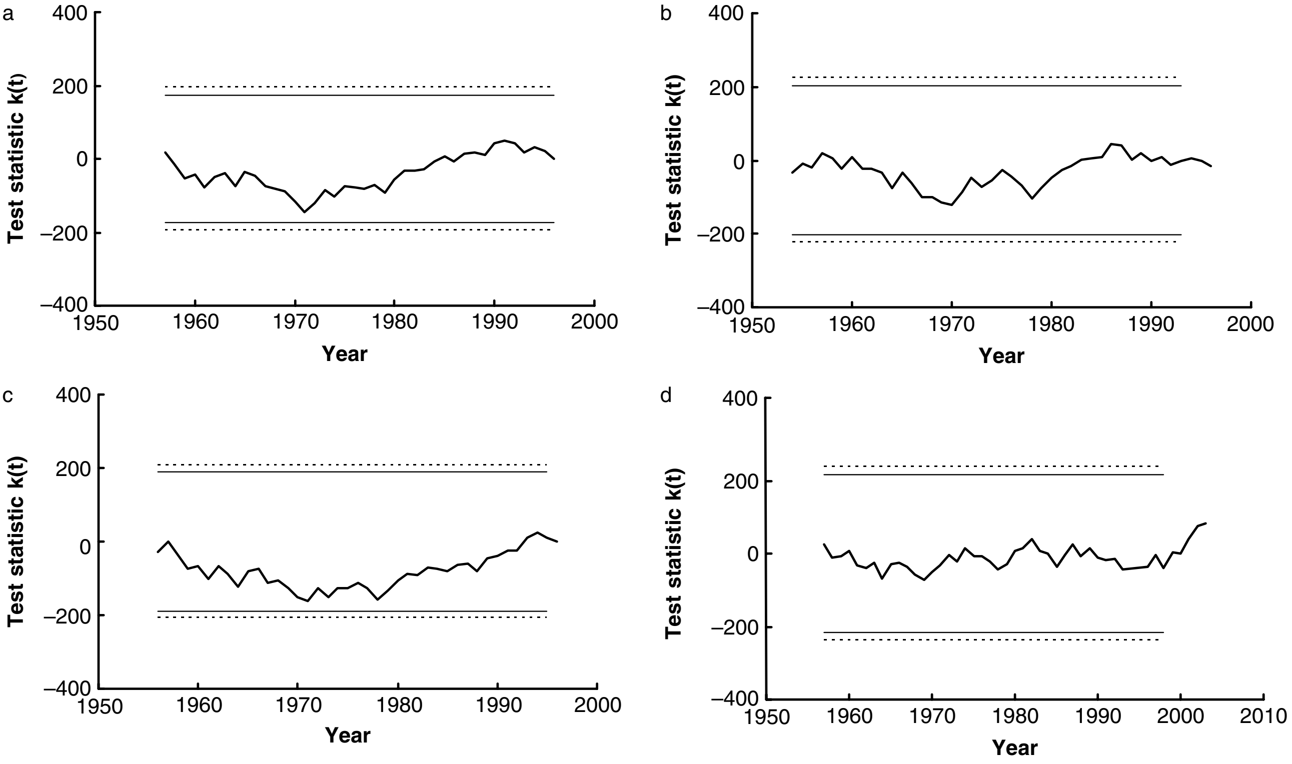

Figure 3. The Pettitt test for detecting a change in the mean of annual precipitation for the (a) Jialu, (b) Qiushui, (c) Tuwei, and (d) Yanhe catchments. Horizontal lines represent the 5% (dotted) and 10% (solid) significance levels

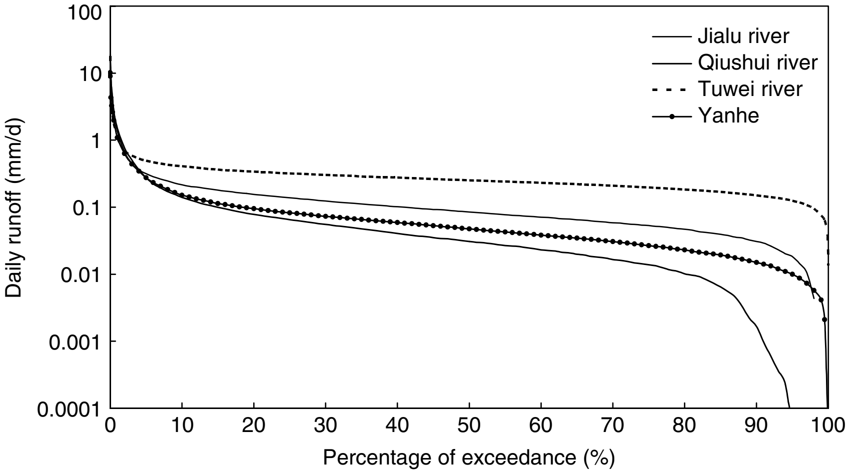

Figure 4. Daily flow duration curves for the whole period of record

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Q_{10} and Q_{90}, indicating little relative variability in daily stream flow. Three of the catchments were perennial, whereas the Qiushui River catchment was ephemeral and flowed 94% of the time. To examine daily stream flow variability further, we define high flows as flows that exceed 5%, i.e. Q_5, and low flows as being 95%, i.e. Q_{95}. The ratio of these extreme flows to median stream flow Q_{50} is a measure of stream flow variability; these ratios are listed in Table V.

The high flow index Q_5/Q_{50} varies between 2·0 and 9·0 across the catchments, with the Qiushui River catchment showing much greater variability. The low flow index $Q_{95}/Q_{50} = 0$ for the Qiushui River catchment, as the stream ceases to flow at or below 95% of the time, whereas for the Tuwei River catchment the ratio is 0·5. Of the four catchments studied, the Tuwei River catchment showed minimum stream flow variability, whereas maximum stream flow variability was observed in the Qiushui River catchment.

Effects of soil conservation measures on daily flow duration curves

Based on the Pettitt test, daily stream flow records were divided into two periods, termed ‘baseline’ and ‘treated’. Data from the baseline period (when there was no significant change in annual stream flow due to soil conservation measures) is used as the basis for comparison with the treated period (when significant change in annual stream flow occurred). The baseline period is from 1957 to 1977 and the treated period is from 1978 to 2003. It should be noted that no change point was found for the Yanhe River catchment based on the Pettitt test; however, for a comparison with the other catchments, it was assumed that the annual stream flow can be divided into two periods with a change point in 1978.

Table V. Characteristics of daily flow duration curves

Index	Jialu	Qiushui	Tuwei	Yanhe
Median flow Q_{50} (mm day^{-1})	0·085	0·031	0·252	0·047
High flow Q_5/Q_{50}	3·7	9·0	2·0	5·8
Low flow Q_{95}/Q_{50}	0·2	0·0	0·5	0·2

Daily stream flows were normalized by average daily precipitation for the two periods to minimize the effect of the precipitation non-stationarity. Figure 5 shows the daily flow duration curves for the baseline and treated periods. The relative reductions in daily flow with the same percentile and their characteristic ratios are listed in Table VI. The reductions in flow were relatively constant, except for extremely high and low flows. The Tuwei and Jialu river catchments showed more uniform stream flow reduction of 20% in most flows, whereas the reduction in the Qiushui River catchment was more dramatic, with most flows reduced by 45% and low flows were reduced by 100%, resulting in zero-flows. The change in FDC for the Yanhe River catchment is somewhat different, with increases in the 40th to 98th percentile flows. Median daily flow reduced between 13 and 54% across the four catchments (Table VI), whereas the coefficient of variation decreased between 11 and 32% except for the Qiushui River catchment, which showed a 12% increase in the coefficient of variation.

The reductions in high and low flows are variable. The high flow index Q_5/Q_{50} in the treated period reduced by

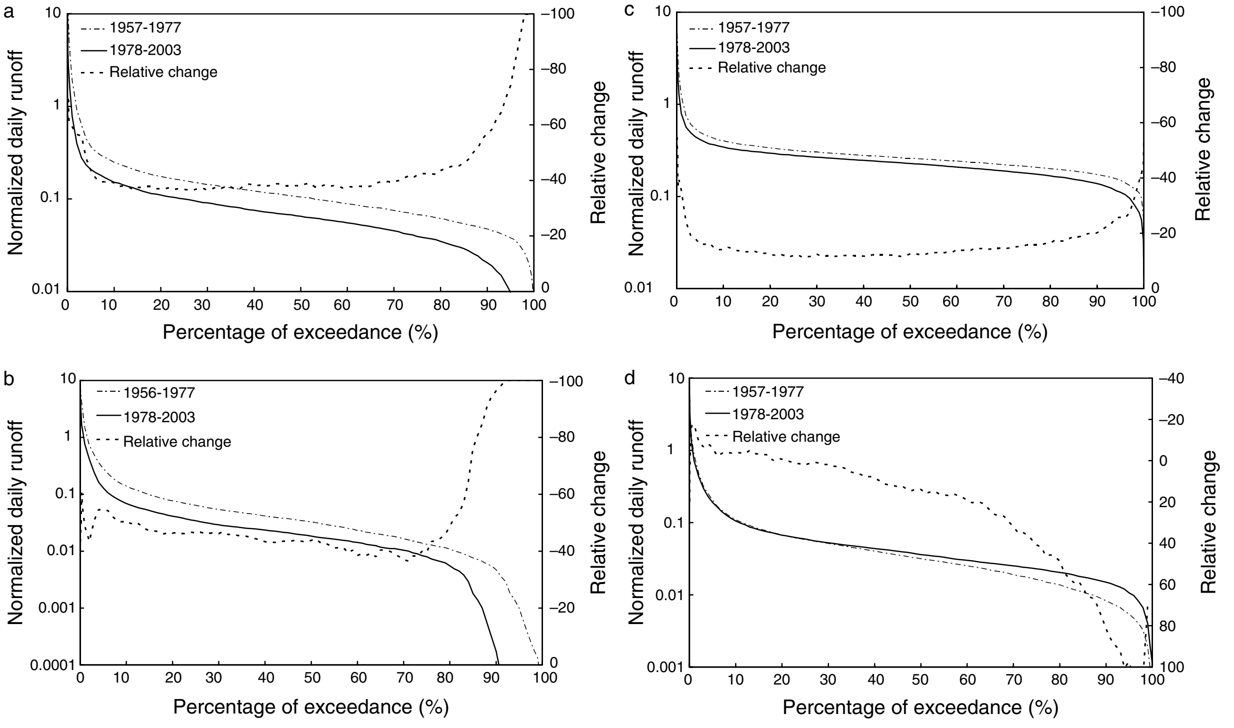

Figure 5. Comparison of daily flow duration curves for: (a) the Jialu River catchment; (b) the Qiushui River catchment; (c) the Tuwei River catchment; (d) the Yanhe River catchment

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Table VI. Comparison of stream flow characteristics during the baseline (start year: 1957; end year: 1977) and treated (start year: 1978; end year: 2003) periods

	Jialu		Qiushui		Tuwei		Yanhe	
	Baseline	Treated	Baseline	Treated	Baseline	Treated	Baseline	Treated
Q_{50} (m^3 s^{-1})	2·94	1·33	3·16	1·54	13·2	9·1	7·22	6·47
CV	3·99	2·77	4·52	4·74	1·22	0·85	3·35	2·98
Q_5/Q_{50}	3·52	3·20	8·68	7·06	1·90	1·83	6·68	5·29
Q_{95}/Q_{50}	0·36	0·15	0·03	0·00	0·57	0·49	0·17	0·28

Note: CV is the coefficient of variation in annual stream flow.

about 20% for the four catchments except for the Tuwei River catchment, which only showed a 3% reduction in the high flow index. The change in low flow index Q_{95}/Q_{50} is much more dramatic; it varies between 14 and 100%. It should be noted that the Yanhe River catchment showed a 64% increase in the low flow index against the general trend of decreased low flow from the other catchments.

Changes in daily flow duration curves over time

To investigate the nature of the changes in the stream flow regime further, daily FDCs for each decade were constructed as shown in Figure 6a–d. A common feature of the FDCs in three of the catchments is the progressive reduction in flow over time (see Figure 6a–c). For the Jialu and Qiushui river catchments, major changes in the FDC occurred during the 1990s, leading to the occurrence of cease-to-flow. There was little change in the FDC during the 1960s and 1970s in the Tuwei River catchment (see Figure 6c). However, changes in the Yanhe River catchment indicated an increase in stream flow, especially in the low flows (Figure 6d).

The characteristic flows during these periods are listed in Table VII. It is clear that the Qiushui River catchment ceased to flow in the 1990s. Changes in median stream flow Q_{50} over the four catchments were between 2 and 34%, whereas low flows showed much greater reduction. It is also clear that the Jialu and Qiushui river catchments experienced more changes in flow during the 1990s than in the other periods (see Figure 6).

DISCUSSION AND CONCLUSIONS

This study evaluated changes in stream flow regime for selected catchments in the Loess Plateau following large-scale soil conservation measures. These measures were

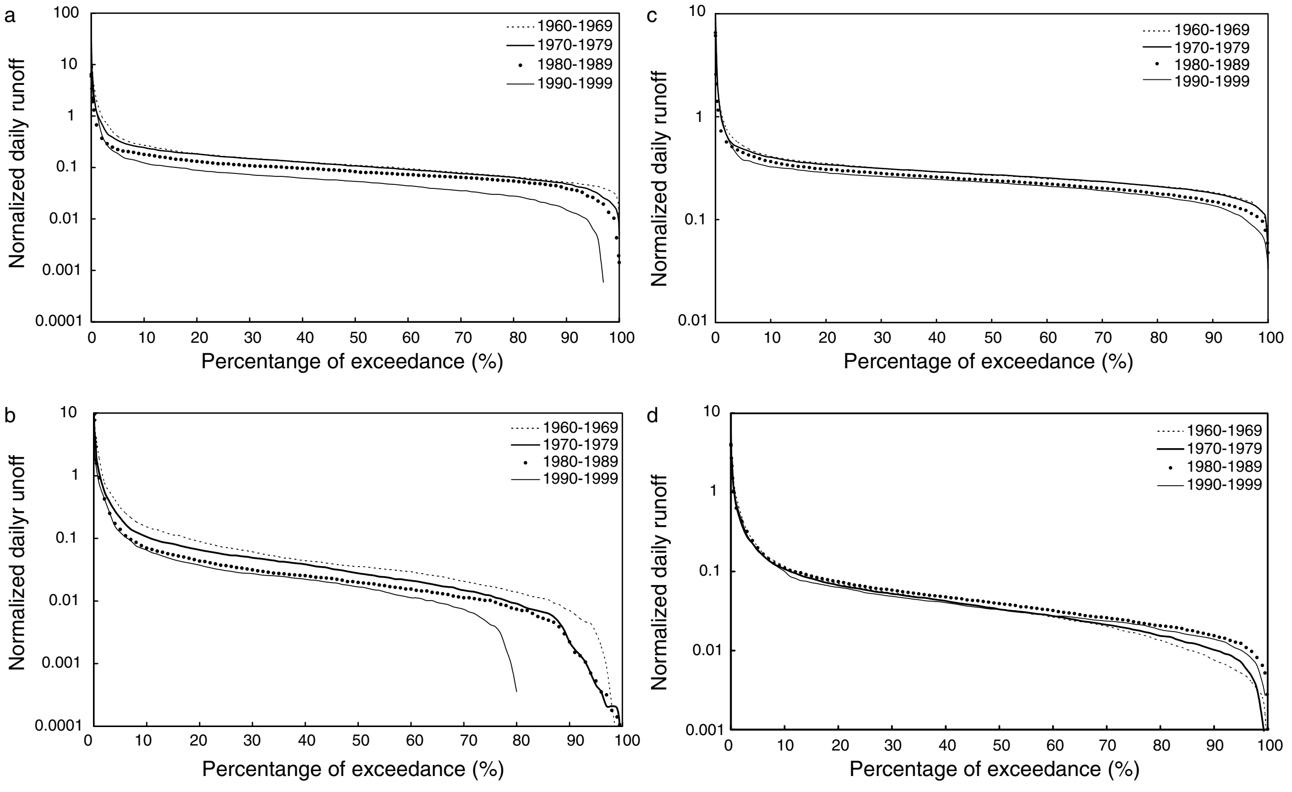

Figure 6. Changes in daily flow duration curves over time for: (a) the Jialu River catchment; (b) the Qiushui River catchment; (c) the Tuwei River catchment; (d) the Yanhe River catchment

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Table VII. Characteristic flows during different periods

Catchment	Index	1960s	1970s	1980s	1990s
Jialu	Q_{50} (mm day^{-1})	0·11	0·11	0·08	0·05
	Q_5/Q_{50}	3·65	3·13	2·69	3·49
	Q_{95}/Q_{50}	0·40	0·32	0·31	0·12
Qiushui	Q_{50} (mm day^{-1})	0·04	0·03	0·02	0·02
	Q_5/Q_{50}	8·71	7·65	7·05	7·41
	Q_{95}/Q_{50}	0·09	0·02	0·03	0·00
Tuwei	Q_{50} (mm day^{-1})	0·27	0·27	0·24	0·23
	Q_5/Q_{50}	1·93	1·78	1·87	1·66
	Q_{95}/Q_{50}	0·60	0·57	0·53	0·47
Yanhe	Q_{50} (mm day^{-1})	0·03	0·03	0·04	0·03
	Q_5/Q_{50}	6·14	5·66	5·08	5·44
	Q_{95}/Q_{50}	0·15	0·22	0·31	0·31

designed to reduce soil erosion, improve agricultural productivity, and enhance environmental quality. There are a number of reported studies on the effects of these measures in reducing average annual stream flow and sediment load (Xu and Niu, 2000; Dai, 2002). Although the purpose of the soil conservation measures is to reduce sediment load, the impact on water yield also needs to be addressed, as the region is limited in water resources. In the last two decades, water demand for agricultural, industrial and urban activities has increased significantly in China (McVicar *et al.*, 2002) and water has become a limiting factor in the region's economic development. It is important that we are able to estimate the impact of the soil conservation measures on stream flow so that economic and social development in the region can be sustained.

Catchments in the Loess Plateau have been under the influence of human activities for centuries, with soil conservation measures accelerating and intensifying in the last four decades. Broadly speaking, the soil conservation measures include engineering works (i.e. terraces and sediment-trapping dams) and vegetation control (i.e. trees and pastures). The effects of these two types of measures on stream flow can vary over time and space. On an area basis, the engineering works occupy much smaller areas than vegetation controls (see Table II). However, the effects of engineering works on runoff may be more significant, as they can more effectively prevent surface runoff.

Most of the terraces in the Loess Plateau are level and they can reduce or stop overland flow and, hence, alter the temporal distribution of stream flow. Dams, including the numerous sediment-trapping dams, can significantly impact stream flow, and their effects can be estimated based on their storage capacities (Zhan and Yu, 1994). It is anticipated that the engineering works are likely to have greater impacts on high flows than are vegetation controls. Attempts have been made to estimate the effects of the individual measures and the methods for doing that remain empirical in nature (Zhang *et al.*, 2002). Among the four catchments studied, the areas under terraces varies between 6 and 42% compared with the total areas occupied by all the soil conservation measures (Table II). Engineering works (terraces and dams) are significant in the Qiushui River catchment, compared with the other catchments, and this may be responsible for the greater stream flow reduction observed in this catchment.

The effect of the vegetation control (e.g. trees) on stream flow has been widely studied (Brown *et al.*, 2005) and simple methods are available for assessing the impact (Zhang *et al.*, 2001). However, given the complex nature of the soil conversation measures in the catchments studied, it is difficult to isolate the effects of individual treatments. Nevertheless, it can be argued that afforestation is the dominant vegetation control on runoff in these catchments, given that the areas occupied by pasture are much smaller (Table II). Huang and Zhang (2004) offered some explanation of the changes in stream flow regime in one of the catchments in this region, attributing the reduction in mean annual runoff to afforestation.

The soil conservation measures in this region are intensive and have modified the stream flow characteristics in the last 50 years. The results indicate that significant changes in annual stream flow occurred in 1978 for the Jialu, Qiushui, and Tuwei river catchments, at the 5% significance level. These catchments showed strong decreasing trends in annual stream flow during the period 1979 to 2003. The exception to this is the Yanhe catchment, where a slight increase in annual stream flow has been found, but the Pettitt test failed to detect a change point in the annual stream flow. The land-use change in these catchments has a long history, dating back to the 1950s. During this period, engineering works such as terraces and dams have been constructed, together with biological measures such as plantations and pasture-lands. These measures have been implemented at a variable rate, e.g. the rate of change was low before 1980 in Tuwei and accelerated after that. The impact of the engineering works on stream flow depends on the location and storage capacity. Given the complex nature of the land-use change in these catchments, it is very difficult to quantify the effect of individual measures on stream flow directly. However, it is possible to estimate the combined effects of the engineering works and biological measures on annual stream flow. The use of the Pettitt approach was to identify the timing of significant annual stream flow change. Engineering works will have a quite immediate impact on stream flow. However, we suspect that the effect will not be linearly related to the area affected by these measures, and this means that the times of large expansion in soil conservation measures may not correspond to the times of significant changes in stream flow. It is quite possible that a threshold exists beyond which the impact on stream flow is significant. In this case, it is the accumulated area that affects annual stream flow. The results from this study indicate that this threshold value is between 7 and 15% for these catchments. For example, 1978 corresponds to 15% of the area implemented in Jialu, 14% in Qiushui, and 7% in Tuwei. It can be argued that the change point of 1978 detected is consistent with the soil conservation measures in three of the catchments.

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Apart from the soil conservation measures, climate is another factor influencing stream flow of the catchments, and interactions between these factors may not be easily separated. Annual precipitation in the catchments showed no significant trends during the period of record (see Table IV), and this suggests that observed annual stream flow trends can be attributed mainly to the soil conservation measures. But it is unclear why an increase in annual stream flow occurred in the Yanhe River catchment. An examination of the FDCs for the catchment revealed that, during the second period, an increase in low flows occurred while the high flows remained constant (Figure 5d). The annual precipitation stationarity does not remove its impact on the stream flow regime, as the distribution of precipitation can also influence stream flow regime. Removing the effect of variability in precipitation on stream flow regime requires more detailed analyses (Lane *et al*., 2005), and the impacts of soil conservation measures on stream flow regime are likely to change with precipitation distribution (i.e. dry years and wet years will respond differently).

The FDCs for the whole period of record showed that the stream flow regime for the Jialu River catchment is similar to that of the Yanhe River catchment, with little variability for flows between 10 and 90% exceedance level. Stream flow in the Tuwei River catchment is even more constant, with the flow index varying between 2·0 to 0·5 for high and low flows. The Qiushui River catchment showed greater variability in stream flow and has recently become ephemeral; this change is mostly attributed to the implementation of the soil conservation measures. Occurrence of zero flow in the Qiushui River catchment represents a significant change in its stream flow regime, and it was not anticipated that the soil conservation measures would lead to such a change. In the future, the impact of further soil conservation measures on stream flow regime needs to be acknowledged. The differences in the FDCs exhibited by the four catchments may reflect the effects of soil, geomorphology and land use on runoff generation.

The stream flow regimes of the catchments have been significantly modified by the soil conservation measures, leading to reductions in stream flow. It can be expected that the reduction in most flows for catchments in this region varies between 20 and 45%. However, the reduction in low flows tends to be more dramatic. Three of the catchments studied showed decreased a coefficient of variability, and one showed the opposite trend. Although changes in the FDCs are progressive, significant changes occurred in the 1990s. These changes in FDCs can be associated with the implementation of the soil conservation measures in the catchments. Although the areas affected by the soil conservation measures increased rapidly in the 1990s it is not clear whether these catchments have seen the full effects of the soil conservation measures, as afforestation requires some years to exercise control over the water balance and there is some lag time between change to surface and groundwater processes and stream flow response at the catchment outlets.

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