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1                   **Trends of streamflow, sediment load**  
2                   **and their dynamic relation for the**  
3                   **catchments in the middle reaches of**  
4                   **the Yellow River over the past five decades**

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9

1 **Abstract**

2 To control severe soil erosion on the Loess Plateau, China, a great number of soil con-  
3 servation measures have been implemented since 1950s and subsequently, the “Grain for  
4 Green” project has been implemented from 1999. The measures and the project re-  
5 sult in a large scale land use/cover change (LUCC). Understanding the impacts of the  
6 measures and the project on streamflow, sediment load and their dynamic relation is  
7 essential as the three elements are closely related to the sustainable catchment man-  
8 agement strategy on the Loess Plateau. The data for seven selected catchments in  
9 the middle reaches of the Yellow River were used and standardized with the precipitation  
10 and the controlling area for analysis. Nonparametric Mann-Kendall test and Pettitt test  
11 were employed to detect trends and change points of the annual streamflow and an-  
12 nual sediment load. Simple linear regressions for the monthly streamflow and sediment  
13 load from May to October were made to express their relationship. Based on the  
14 change point identification and the time when the project began to implement on the  
15 Loess Plateau, the whole time for the data records was divided into three periods to  
16 compare the change degrees of streamflow, sediment load and their relation  
17 for the catchments.

18 Results show that there are three types of responses in streamflow, sediment load,  
19 and their dynamic relations for the seven catchments. The effects of the LUCC on  
20 streamflow, sediment load, and their relationships are greatest in the three transi-  
21 tion zone catchments with the two rocky mountain catchments followed. The effects are  
22 much weaker in the two loess hilly-gully catchments. In general, the change degrees for  
23 sediment load are much greater than those for streamflow, which results from the  
24 decreased streamflow and weakening trend of their dynamic relation period by period in  
25 catchments.

26  
27 **Key words:** *Streamflow, Sediment load, Dynamic relation, Soil and water conservation,*  
28 *“Grain for Green” project, Catchment, Middle Reaches of Yellow River*

29

## 1 **1 Introduction**

2 The Loess Plateau of 620 000 km<sup>2</sup> is located in the middle reaches of the Yellow River  
3 (750,000 km<sup>2</sup>). It is characterized with heavily dissected landscape and severe soil loss  
4 resulted from wind-deposited loess soils, sparse vegetation, intense rainfall, and long  
5 agricultural history. To control the severe soil erosion, a number of soil conservation  
6 measures have been implemented on the Loess Plateau since the 1950s (Ye *et al.*, 1994;  
7 Zhang *et al.*, 1998; Ran *et al.*, 2000), which mainly include afforestation, pasture  
8 reestablishment, terracing and sediment trapping dams. The measures resulted in great  
9 land use and land cover changes (LUCC) and dramatically altered hydrological regimes and  
10 significantly reduced sediment load in the Yellow River (Zhu, 1960; Liu and Zhong, 1978;  
11 Ran *et al.*, 2000; Zhang *et al.*, 2008; Rustomji *et al.*, 2008). Apart from these, human  
12 activities in last five decades, such as population growth, increasing irrigation areas,  
13 reservoirs construction, industry development and coal mining, aggravated water  
14 resources crisis on the Loess Plateau (Liu and Zhang, 2004; Fu *et al.*, 2004) and  
15 simultaneously affected sediment transport regime (Wang *et al.*, 2007). The climate  
16 change has affected the Yellow River basin with the noted increase in minimum  
17 temperature and no appreciable change in precipitation in the last 50 years (Fu *et al.*,  
18 2004). Although the sensitivity of streamflow to precipitation, temperature or potential  
19 evapotranspiration was detected (Fu *et al.*, 2007; Zheng *et al.*, 2007), human activities  
20 were believed to be the primary driving force to the trends of streamflow and sediment  
21 load in the catchments and the main stream of Yellow River basin (Ran *et al.*, 2000; Liu and  
22 Zhang, 2004; Fu *et al.*, 2004 and 2007; Li *et al.*, 2004; Wang *et al.*, 2007; Zheng *et al.*, 2007;  
23 Zhang *et al.*, 2008; Runstomji *et al.*, 2008; Gao *et al.*, 2011).

24 It is well known that afforestation and biophysical measures can alter catchment's water  
25 balance by increasing rainfall reception and evapotranspiration (Zhang *et al.*, 2001; Brown  
26 *et al.*, 2005). Soil erosion and sediment transport are therefore decreased through  
27 decreasing surface runoff and increasing water infiltration into soil (Colman, 1953; Morgan,  
28 1986; Sahin and Hall, 1996; Castillo *et al.*, 1997; Quinton *et al.*, 1997). Huang and Zhang  
29 (2004), Mu *et al.* (2007), and Zhang *et al.* (2008) found that changes in streamflow tended  
30 to be relatively uniform across the flow spectrum with typical reductions of 30-60% in the  
31 catchments in the region due to soil conservation measures. From the 1980s, a great  
32 number of researches have been conducted and the results showed that sediment load in  
33 the catchments on the Loess Plateau tended to manifest a significantly negative trend and  
34 sediment retention benefit was estimated with soil and water conservation measures  
35 (Chen, 1988; Tang *et al.*, 1993; Wang and Wu, 1993; Ye, 1994; Yu, 1997; Zhang *et al.*, 1998;  
36 Ran *et al.*, 2000; Wang and Fan, 2002; Yao *et al.*, 2005 and 2010). Runoff-sediment  
37 behaviors are also believed to change because of the mechanisms of afforestation and  
38 check dams. As the change of sediment yield from a catchment probably resulted from  
39 one or both variables of suspended sediment concentration and discharge, how the  
40 sediment concentration change has been noted by the researchers. Xu (2002) and Liao *et al.*  
41 (2008) showed that the frequency of hyperconcentration flow, the main form of  
42 sediment transportation on the Loess Plateau, was decreased due to the implementation  
43 of soil conservation measures in the region.

44

1 Rustomji *et al.* (2008) showed that mean annual sediment concentration in 7 of 11  
2 catchments exhibited a statistically significant decreasing trend over time. A few  
3 researches focused on the relationship between streamflow and sediment load. However,  
4 the results were complex and inconsistent. Zheng and Cai (2007) concluded that increasing  
5 vegetation coverage didn't change the relationship between streamflow and sediment  
6 load in the paired catchments. **However an opposite conclusion** was drawn from Liu *et al.*  
7 (2010), who showed that the relationship between streamflow and sediment load  
8 changed obviously with land use change in another paired catchments under heavy  
9 rainfall and high rainfall intensity. Rustomji *et al.* (2008) showed that although the results  
10 from the sediment rating curves based on the daily data support the conclusion of the  
11 variations of annual suspended sediment concentration, the soil conservation measures  
12 seemly did not significantly change the sediment rating curves in two years with the  
13 similar precipitation in two catchments on the Loess Plateau. Pan *et al.* (1999) indicated  
14 that the relationship between streamflow and sediment load in flood season did not  
15 change essentially in a region with area of  $11 \times 10^4 \text{ km}^2$  on the Loess Plateau.

16 Above researches indicate that LUCC resulted from soil conservation measures can  
17 affect hydrological regimes and in turn, sediment transport processes in a catchment. But  
18 it is not very clear how the soil conservation measures affect the relationships between  
19 streamflow and sediment load in a catchment. The inconsistent results are probably due  
20 to the data used, specific landform of the studied area, age and type of vegetation, soil  
21 characteristics, rainfall intensity, spatial scale focused on, and mixed nature of historic soil  
22 conservation measures. Obviously further researches are needed in this field. Furthermore,  
23 the "Grain for Green" project has been widely implemented from 1999. It is so important  
24 to fully understand the impacts of soil conservation measures and vegetation restoration  
25 on streamflow, sediment load, and runoff-sediment behaviors in the region to provide an  
26 integrated estimate for the effects of soil conservation measures on hydrology and  
27 sediment transportation and help ecological management in the catchments on the Loess  
28 Plateau. Therefore, the specific objectives of this study were to (1) examine the trends and  
29 change points of annual streamflow and annual sediment load over the last 50 yr in seven  
30 selected catchments on the Loess Plateau; (2) find the changes in the streamflow and  
31 sediment load represented by monthly flow/ sediment duration curves; and (3) investigate  
32 the changes in the dynamic relation of streamflow to sediment load in different periods in  
33 the catchments.

## 34 **2 Study area**

35 The coarse sand hilly catchments (CSHC) with a total area of  $1.13 \times 10^5 \text{ km}^2$ , on the Loess  
36 Plateau, are recognized as the main source of coarse sediment ( $> 0.1 \text{ mm}$ ) on downstream  
37 bed (Fig.1). Average annual precipitation in the CSHC is 456 mm varying from more than  
38 600 mm in the southeast to less than 300 mm in the northwest. About 78% of annual  
39 precipitation occurs from May to October. The northwestern part of the CSHC is  
40 considerably flat and the southeastern part is characterized by a heavily dissected  
41 landscape with  
42

1 gully densities ranging from 2 to 8 km.km<sup>-2</sup> (Chen et al.,1988; McVicar et al., 2007).  
2 The wind-deposited loess soils developed during Quaternary period cover the study  
3 area with thickness of 50- 200 m. Coarse sandy soils are common in the northwest  
4 and finer clay-rich soils occur in the southeast.

5 Totally, seven catchments within the CSHC were selected for the purpose of  
6 study, and details of which are given in Table 1. Three catchments are located in the tran-  
7 sition zone from the flat sandy area in northwest to the hilly-gully area in the middle of  
8 the CSHC. Two catchments are in the loess hilly-gully area and other two, in the rocky  
9 mountain area in the south. Pasture is the dominant vegetation type in the three tran-  
10 sition zone catchments and forest dominates the two rocky mountain catchments. In  
11 the two loess hilly-gully catchments, vegetation type is characterized with transitional  
12 features from forest to steppe.

13 The areas for historic soil conservation measures in the seven catchments are given  
14 in Table 2, which were obtained through census (Ran et al., 2000). The areas of ter-  
15 races, afforestation, pasture land, and sediment-trapping dams all increased from 1959  
16 to 1996. The increased rates were the greatest in the 1970s and 1980s. The vegetation  
17 coverage, represented by NDVI, was found to have an increasing trend at  $P < 0.05$  sig-  
18 nificance level on the Loess Plateau in the last 20 yr due to the “Grain for Green” project  
19 implementation (Xin et al., 2007; Sun et al., 2011).

## 20 **3 Data and methods**

### 21 **3.1 Data Description**

22 Monthly streamflow and sediment load data in the seven catchments were obtained  
23 from the Water Resources Committee of the Yellow River Conservancy Commission of  
24 China (Table 1). Monthly precipitation data were obtained from the State Meteorology  
25 Bureau of China. Monthly precipitation data are spatially interpolated using ordinary  
26 Kriging method (Wan et al., 2011). Area-weighted method is used to compute the  
27

1 monthly precipitation in each catchment. Monthly streamflow, sediment load and pre-  
 2 cipitation data are then accumulated to annual totals. To reduce the effects of precipi-  
 3 tation and drainage area on the analysis of streamflow and sediment load for the  
 4 catchments of different size, the volumes of annual/ monthly streamflow and sediment  
 5 load are standardized by the controlling area and the precipitation in corresponding time.  
 6 So a unit for streamflow is “ $m^3.km^{-2}.mm^{-1}$ ”, which is dimensionless, the value is 1000 times  
 7 the runoff coefficient and means the runoff availability ( $m^3$ ) per  $km^2$  area per mm  
 8 precipitation in a catchment in a given period. And a unit for sediment load, “ $t.km^{-2}.mm^{-1}$ ”,  
 9 actually signifies sediment availability (t) per  $km^2$  area per mm precipitation in each  
 10 catchment in a given period.

### 11 3.2 Trend test and change point analysis

#### 12 3.2.1 Mann-Kendall test and Pettitt test

13 Nonparametric Mann–Kendall method proposed by Mann (1945) and improved by  
 14 Kendall (1975) is widely used to test trends in hydrological and climatological time  
 15 series, mainly because it is simple, robust, and can handle the values missed or below  
 16 the detection limits (Xu *et al.*, 2005; Bi *et al.*, 2009). The method has been recom-  
 17 mended by the World Meteorological Organization (1988) as a standard procedure for  
 18 detecting trends in hydrological data that are serially independent (Hamed and Rao,  
 19 1998).

20 In Mann–Kendall test, the null hypothesis,  $H_0$ , is that the observations,  $x_i$  ( $i =$   
 21  $1, 2, \dots, j, k, \dots, n$ ), are independent and identically distributed. The alternative hypoth-  
 22 esis,  $H_1$ , is that a monotonic trend exists in  $x_i$ . The Mann–Kendall test statistic,  $S$ , is  
 23 calculated using the formula:

$$24 \quad S = \sum_{j=1}^{n-1} \sum_{k=j+1}^n \text{sgn}(x_k - x_j) \quad (1)$$

25

$$\text{sgn}(x_k - x_j) = \begin{cases} 1 & x_k - x_j > 0 \\ 0 & x_k - x_j = 0 \\ -1 & x_k - x_j < 0 \end{cases} \quad (2)$$

where  $n$  is the number of observed data series, and  $x_j$  and  $x_k$  are the values in periods  $j$  and  $k$  ( $k > j$ ), respectively. For  $n \geq 10$ , the statistic,  $S$ , is approximately normally distributed with the mean and variance:

$$E(S) = 0$$

$$\text{VAR}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (3)$$

where  $q$  is the number of tied groups and  $t_p$  is the number of data values in the  $p$ th group.

The standard test statistic,  $Z$ , is computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

The statistic,  $Z$ , follows the standard normal distribution. If  $|Z| \geq Z_{1-\alpha/2}$ ,  $H_0$  is rejected and a significant trend exists in the observed time series. A positive value of  $Z$  indicates an upward trend and a negative value of  $Z$ , a downward trend.

Trend magnitude is estimated using a nonparametric median based slope method proposed by Sen (1968) and extended by Hirsch *et al.* (1982):

$$\beta = \text{Median} \left[ \frac{X_k - X_j}{k - j} \right] \quad \text{for all } j < k. \quad (5)$$

where  $1 < j < k < n$ .  $\beta$  is the median of all possible combinations of pairs for the whole data set.

Nonparametric Pettitt test is used in this study for detecting a change point in the data series. The test is a kind of distribution-free method and allows minimum assumptions to be made about the data. Therefore, it is particularly suited to hydrological series. The test is robust, simple and relatively powerful (Kundzewicz and Robson, 2004). Pettitt test uses a version of the Mann-Whitney statistic,  $U_{t,N}$ , that verifies if two samples of  $x_1, \dots, x_t$  and  $x_{t+1}, \dots, x_N$  are from the same population. The test statistic,  $U_{t,N}$ , is given by

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^N \text{sgn}(x_t - x_j) \quad \text{for } t = 2, \dots, N \quad (6)$$

where  $\text{sgn}(\theta) = 1$  if  $\theta > 0$ ;  $\text{sgn}(\theta) = 0$  if  $\theta = 0$ ;  $\text{sgn}(\theta) = -1$  if  $\theta < 0$ .

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. Its statistic  $k(t)$  and the associated probabilities used in the significance testing are:

$$k(t) = \max_{1 \leq t \leq N} |U_{t,N}| \quad (7)$$

$$\text{and } P \cong 2 \exp \left\{ -6(k_N)^2 / (N^3 + N^2) \right\} \quad (8)$$

Additionally, sequential Mann-Kendall test is also used to validate the result of change point detected with Pettitt test in the time series of streamflow and sediment load. It is also helpful to compare the results of change point tested by the non-parametric methods with the original data series to determine the change point used in this study.

**3.2.2 Serial Correlation Test**

Serial correlation has the effect on Mann-Kendall test. The existence of positive autocorrelation in data increases the probability of detecting trends when actually none exists (Partal and Kahya, 2006). Thus, the time series should be ‘pre-whitened’ to eliminate the effect of serial correlation before applying Mann–Kendall test. The lag 1 serial correlation coefficient,  $r_1$ , is calculated to detect the autocorrelation of the data used in the study. The lag-1 autocorrelation is the correlation between  $x_i$  and  $x_{i+1}$ . It has the formula:

$$r_1 = \frac{\sum_{i=1}^{N-1} (x_i - \bar{x})(x_{i+1} - \bar{x})}{\sum_{i=1}^N (x_i - \bar{x})^2} \tag{9}$$

where  $N$  is the length of the time series,  $x_i$  is the value of the time series at time  $t$ , and  $\bar{x}$  is the overall mean of  $x_i$ .

The significance of  $r_1$  can be estimated using the one-tail 95% significance of the Gaussian distribution (WMO 1966):

$$r_k(95\%) = \frac{-1 \pm 1.96\sqrt{N - k - 1}}{N - k} \tag{10}$$

where  $k$  is the time lag and  $r_k$  is the autocorrelation coefficients at the time lag of  $k$ .

The critical values of the calculated lag-1 serial correlation coefficient,  $r_1$  at the 5% significance level are -0.288 and 0.249. Thus, if  $r_1$  is out of the interval, the lag-1 autocorrelation is statistically significant. If  $r_1$  is not significant at the 5% level, Mann–Kendall test is applied to original values of the time series. Few series (less than 5%) in the data set used in the study appear to have significant lag-1 serial correlation coefficient. So, Mann–Kendall test is applied to test the trends of the time series in our study.



## 4 Results and discussion

### 4.1 Trends, change points and relative changes for annual streamflow

Annual streamflow (with unit of  $\text{m}^3 \cdot \text{km}^{-2} \cdot \text{mm}^{-1}$ ) in the five catchments except the two loess hilly-gully catchments presented negative trends by Mann-Kendall test with statistically significance level, in which four catchments were detected at  $p < 0.001$  and one at  $p < 0.05$  (Fig.2, Table 3). Average change rate of annual streamflow was -3.39 per year in the three transition zone catchments, but only -0.67 per year in the two rocky mountain catchments. Average change rate for the former was about 5 times that for the latter. However, the two loess hilly-gully catchments, i.e., Qinjian and Yanhe catchments, were an exception. Change rate of the annual streamflow in Qinjian catchment manifested a slightly increasing trend, but in Yanhe catchment, a slightly decreasing trend, both of which were statistically insignificant.

The change Points detected by Pettitt test and sequential Mann-Kendall test for annual streamflow in the five catchments were generally highly consistent and had a statistically significant level. To the difference of change point tested by two methods in Kuyehe River, the result detected by Pettitt test was considered to be rational as compared with the original data series (Figure 2 and Table 3). The change points for Kuye, Jialu, and Tuwei catchments in the transition zone occurred in 1981, 1982 and 1983 and for Yunyan, Shiwang catchments in the rocky mountain area, in 1995 and 1988, respectively. The reason for the different change points is probably related to the time when the cumulative area for soil conservation measures in the catchments reached about 15%. Results from Ran *et al.* (2000), Yao *et al.* (2004) and Xu and Sun (2006) implied that such a percentage of the area for soil conservation measures can significantly affect hydrological cycling and sediment retention or transportation in a catchment.

According to the change points for the five catchments and in consideration of the implementation of “Grain for Green” project after 1999, the whole time period for streamflow data is divided into three periods: period 1 (pre-change point year period, abbreviated to P1), period 2 (post-change period from pre-change point year to 1999, P2), and period 3 (“Grain for Green” period from 2000 to 2005, P3). Monthly flow duration curves were derived and relative changes of streamflow at high(5%), median(50%) and low(95%) percentiles in P2 and P3 are listed in Table 4, as compared to P1.

1 From Table 4, relative changes of streamflow were negative except for the two  
2 loess hilly-gully catchments, i. e., Qinjian and Yanhe catchments. Change degrees,  
3 whenever in P2 or P3, were higher in the three transition zone catchments than those in  
4 the two rocky mountain catchments.

5 Change degrees of streamflow in the transition zone catchments were not only greater  
6 in P3 than those in P2, but also much greater than those in the rocky mountain  
7 catchments in P3. Average relative changes for the three transition zone catchments in P3  
8 reached 72.5%, 58.4%, and 57.3% at the high(5%), median(50%), and low(95%) percentile  
9 flows, respectively. Moreover, average relative changes for the two rocky mountain  
10 catchments in P3 were 46.1%, 48.3%, and 50.4% at the same percentiles, respectively.  
11 That means that the implementation of soil conservation measures exerted greater effects  
12 on the transition zone catchments than the rocky mountain catchments, especially in P3  
13 when the “Grain for Green” project was implemented.

14 Change degrees were much weaker for the two loess hilly-gully catchments, i.e., Qinjian  
15 and Yanhe catchments. The result is consistent with the trend detection for the five  
16 catchments.

#### 17 **4.2 Trends, change points and relative changes for annual sediment load**

18 Like annual streamflow, annual sediment load in the five catchments except the two loess  
19 hilly-gully catchments showed statistically significant decreasing trends and change points  
20 (Table 5). Average change rate of annual sediment load in the three transition zone  
21 catchments was  $-0.5547 \text{ t.km}^{-2}.\text{mm}^{-1}.\text{a}^{-1}$ , and in the two rocky mountain catchments, only  
22  $-0.0540 \text{ t.km}^{-2}.\text{mm}^{-1}.\text{a}^{-1}$ . Clearly, average change rate for the former was nearly 10 times  
23 that for the latter.

24 Change points of annual sediment load were detected by Pettitt test and sequential  
25 Mann-Kendall test and the results were generally consistent with each other except for  
26 Kuyehe River and Tuweihe River. As compared with the original data series of the  
27 catchments, change points detected by Pettitt test were considered to be rational, as  
28 shown in Table5. It is clear that change points of annual sediment load occurred also  
29 earlier in the three transition zone catchments, from 1977 to 1979, Whereas change  
30 points in the two rocky mountain catchments occurred later, both in 1982 (Table 5).  
31 Compared to Table 3, change points of annual sediment load in the five catchments were  
32 close to those of annual  
33

1 streamflow except Yunyan catchment, which implies that the effects of controlling soil  
2 erosion and sediment yield in these catchments have been achieved through the surface  
3 runoff reduction by soil conservation measures. To investigate relative changes in annual  
4 sediment load in all the seven catchments, the three periods are identified for the sediment  
5 load data using the same period division criteria as those for annual streamflow (Table 6).

6 Table 6 shows that compared to P1, relative changes of sediment load in all the seven  
7 catchments were negative at the high(5%), median(50%), and low(95%) percentiles of  
8 sediment transport regime in the two latter periods. Days of zero sediment load increased  
9 in all the catchments, including the two loess hilly-gully catchments.

10 For the three transition zone catchments, average relative changes at the high  
11 (5%), median (50%) and low (95%) percentile sediment load in P2 were 56.0%, 60.2%, and  
12 33.5% and in P3, 93.7%, 88.6%, and 71.8%, respectively. There were considerable  
13 differences in the relative change between the two periods. For the two rocky mountain  
14 catchments, average relative change at high sediment load was 58.9% in P2 and 78.4% in  
15 P3. The result indicates significant effects of soil conservation measures and the “Grain for  
16 Green” project on sediment transportation in the study area. However, the effect of “Grain  
17 for Green” project implementation is much greater than that of soil conservation  
18 measures due to the continuity in the implementation process.

19 Form above two sections, change degrees of annual sediment load were detected to be  
20 much greater than those of annual streamflow in catchments.

#### 21 **4.3 Dynamic relation of streamflow and sediment load in the catchments**

22  
23 Change points of annual sediment load in the seven catchments (Table 5) are referred to  
24 identify the periods and analyze the dynamic relation of streamflow to sediment load.

25 Figure 3 shows a set of scatter diagrams illustrating the relationship between monthly  
26 sediment load and monthly streamflow in the three periods in the seven catchments.

27 Simple linear regression equations presented

28

1 simultaneously. Streamflow and sediment load were showed as X and Y axis variables in  
2 **Figure 3**, respectively. Because no data were recorded in some months in some  
3 catchments, the monthly data of sediment load and streamflow in the flood season from  
4 | May to October were used in the study, so as to make the results comparable.

5 Before analysis of the trend and change of the coefficient of equation, the structure of  
6 linear regression between streamflow and sediment load was tested using Chow test to  
7 see if there was statistical difference in relationships among three periods in each  
8 catchment. Chow (1960) constructed F test to detect the presence of a structural break  
9 and commonly used in time series analysis. The results showed that there was statistically  
10 significant difference with  $p < 0.05$  in relationship between streamflow and sediment load  
11 among periods in six catchments except for Yunyan, one of rocky mountain catchments.  
12 The result was basically consistent with the annual trend test in Table 3 and 5, but the  
13 disagreement between annual trend and monthly relationship in Qingjian, Yanhe and  
14 Yunyan catchments was probably due to the hydrological regime in monthly scale, which  
15 | greatly affected the relationship.

16 The range of the scattered distributions of monthly sediment load against monthly  
17 streamflow in the three transition zone catchments is up to **{2000,1000}**, whereas in the  
18 two rocky mountain catchments, only **{500,100}**. Apparently, the former is much wider  
19 than the latter. The range of the scattered distribution in the two loess hilly-gully  
20 catchments lies in the middle. The other factors, such as frequency of rainstorm,  
21 vegetation coverage, soil and hydrological geology were supposed to determine the  
22 | distribution scope of streamflow and sediment load in catchments (Ran et al., 2000).

23 The regression coefficients (with unit of  $t \cdot m^{-3}$ ) can be considered as “sediment generation  
24 coefficients” because they may indicate the sediment generation capacity in the  
25 catchments. **Figure 3** shows that the linear regression coefficients, in general, are much  
26 higher in the transition zone catchments and the loess hilly-gully catchments than those in  
27 the rocky mountain catchments. The average coefficients in P1, P2 and P3 are 0.4723,  
28 0.3164 and 0.0891 in the three transition zone catchments and 0.5519, 0.4728 and 0.5093  
29 in the two loess hilly-gully catchments, while they are only 0.1513, 0.1336 and 0.0932 in  
30 the two rocky mountain catchments. This indicates that as for per unit of streamflow, the  
31 catchments located in the transition zone and loess hilly-gully area had a stronger capacity  
32 to generate and transport sediment than the catchments in the rocky mountain area. The  
33 reason is apprently related to the high vegetation coverage in the rocky mountain area  
34 catchments, as shown in Table 1.

35 In consideration of standardization of streamflow and sediment load data with  
36 precipaiton and controlling area, human activities such as soil conservation measures  
37 from the 1970s to 1980s and the “Grain for Green” project after 1999 were expected to  
38 make the sediment generation capacity in the catchments to be increasingly negative  
39 trends period by period, except the two loess hilly-gully catchments (Table 7). Compared  
40 to P1, the average reduction rate of linear regression coefficients in P2 was 31.2% in the  
41 transition zone catchments and only 18.0% in the rocky mountain catchments, but in P  
42

1 3, it was up to 83.2% and 60.8%, correspondingly. However, the negative trend was not  
2 evident in the loess hilly-gully catchments. Average reduction in P2 in all the seven  
3 catchments was 22.5% and in P3, 55.4% (Table 7).

4 In this study, the absolute value of a constant (with unit of  $t \cdot km^{-2} \cdot mm^{-1}$ ) in the linear  
5 regression equation for each of the catchments implies existing in-channel sediment  
6 storage in a given period to some extent, which can demonstrate the “sediment  
7 generation capacity” in another way. In P1, much more sediment was stored in the three  
8 transition zone catchments than in the two loess hilly-gully catchments and the two rocky  
9 mountain catchments (Fig.3). Correspondingly, average sediment storages were 68.6, 23.3  
10 and 6.3, respectively. Generally sediment storage in the catchments showed a decreasing  
11 trend period by period except Qingjian catchment in the loess hilly-gully region. Compared  
12 to P1, soil conservation measures adopted in the 1970s and 1980s reduced sediment  
13 storage by 56.9% in the transition zone catchments and the “Grain for Green” project  
14 implementation further reduced it by 95.7%.

15 From the point view of equation, the streamflow volume at which sediment load  
16 equals zero may be understood as the situation in which a given catchment reaches its  
17 scour and silting balance (Fig.3). The standardized streamflow volume at which the  
18 balance is needed for a catchment showed a decreasing trend with the shifted period  
19 in most of the catchments (Table 8). Especially in the three transition zone catchments,  
20 average reduction of the streamflow volume for the balance reached 38.0% in P2 and up  
21 to 80.6% in P3.

22 Compared to P1, the relationship between streamflow and sediment load generally  
23 became poor in the correlation coefficients from P2 to P3, especially in the transition zone  
24 catchments as well as Shiwang catchment, one of the rocky mountain catchments (Fig. 2a,  
25 b, c and g). On the Loess Plateau, human activities are recognized as the primary factor  
26 leading to the negative trends of streamflow and sediment load (Ran *et al.*, 2000; Fu *et al.*,  
27 2004; Zhang *et al.*, 2008; Rustomji *et al.*, 2008; Yao *et al.*, 2010). But human activities are  
28 wide ranging and some of them can potentially increase soil loss in the catchments (Ran  
29 *et al.*, 2000; Wang and Fan, 2002).

30 The implementation of soil and water conservation was expected to control soil erosion  
31 and reduce sediment delivery to the Yellow River (Morgan 1986; Chen *et al.*, 1988). The  
32 “Grain for Green” project implemented since 1999 resulted in a considerable  
33 improvement of vegetation coverage on the Loess Plateau. However, sediment trapping  
34 dams built up in the 1970s and 1980s were easily damaged by heavy rainstorm (Zhang,  
35 1995). The ratio of silted storage to the total storage of reservoir was up to 40% in the  
36 seven catchments (Xiong and Ding, 1994). The variability of sediment concentration in the  
37 catchments in P2 was closely related to the ruined sediment trapping dams and the  
38 release regime of reservoirs (Zhang, 1995; Ran *et al.*, 2000). Moreover, rapid urbanization  
39 and extensive infrastructure construction were simultaneously proceeding in the region  
40 (Liu and Han, 2007), which usually produced a huge amount of sediment deposition and  
41 dreg on the river bed and probably led to a high concentration flow, even in a medium  
42 rain event (Xu, 2002).

43 In consideration of the standardization of the data by precipitation and  
44 catchment area, the decreasing/weakening trends of streamflow, sediment load, and  
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1 their dynamic relation in the catchments were probably related to the characteristics of  
2 soil conservation measures adopted after the 1950s. One was the total controlled area  
3 by soil conservation measures; and the other was the allocation of soil conservation  
4 measures. Xu and Sun (2006) showed that a threshold existed in the area of soil and water  
5 conservation measures in reducing sediment yield in Wudinghe River of the Loess Plateau.  
6 Yao *et al.* (2004) found that if the controlled area by dam-reservoir in a catchment was less  
7 than 10% of the total area, the trend of sediment load reduction would not be significant.  
8 But the differences in the mechanisms of evapotranspiration and hydrologic cycle regime  
9 with different landforms and vegetation coverage degrees probably determined the  
10 intrinsic differences in the trends and change degrees of streamflow and sediment load as  
11 well as their relationship between catchments. Although a number of studies supported  
12 the viewpoint from a single factor, further research is definitely needed to find an  
13 integrated estimate for more catchments. The responses of streamflow and sediment load  
14 to the LUC in Qingjian and Yanhe catchments are different from those in other  
15 catchments. The result agrees with those from Dai and Yan (2002), Zhang *et al.* (2008),  
16 probably due to other kinds of human activities which aggravate soil erosion and increase  
17 sediment transportation in the catchment.

18 **As a whole**, the trends of three indices, *i.e.*, regression equation coefficient, regres-  
19 sion equation constant and the streamflow volume at which a scour and silting bal-  
20 ance reached, are found to be increasingly negative with significant level in most of the  
21 catchments. The decreasing trends indicate that soil conservation measures and the  
22 “Grain for Green” project considerably weakened the sediment yield capacity and the  
23 dynamic relation of sediment load to streamflow in most of study catchments. **On the**  
24 **other hand, it is the trend of streamflow and the weakening trend in relationship between**  
25 **streamflow and sediment load, which resulted in the negative trend of sediment yield in**  
26 **most catchments.**

## 28 **5 Summary**

29 The impacts of soil conservation measures and the subsequent “Grain for Green”  
30 project on streamflow, sediment load, and their dynamic relations were examined for the  
31 seven catchments in the middle reaches of the Yellow River, China. The responses showed  
32 a great variety, but generally three types could be identified based on the spatial  
33 distribution of the catchments. Both annual streamflow and annual sediment load  
34 presented significant negative trends and change points in the three transition zone  
35 catchments and two rocky mountain catchments. In most of the cases, the decreasing  
36 change degrees of streamflow and sediment load in the three sandy transition zone  
37 catchments were greater than those in the two rocky mountain catchments. Change  
38 points detected in the sandy transition zone catchments were earlier than those in the  
39 rocky mountain catchments. Change degrees with the shifted periods in sediment load  
40 were much greater than those in streamflow, especially in the three sandy transition zone  
41 catchments. The implementation of soil conservation measures from the 1970s to 1980s  
42 reduced the sediment generation capability in the catchments by 22.5% and

1 the subsequent “Grain for Green” project since 1999 further reduced it by 55.4%. The  
2 combination of temporal change in streamflow and relationship between streamflow and  
3 sediment load resulted in a statistically significant trend in sediment load in catchments.  
4 The effects of the LUCC on the streamflow, sediment load and their relationships were  
5 much weaker in the two loess hilly-gully catchments, probably due to the other intensive  
6 human activities. The results implies that future catchment management plans for the  
7 CSHC should acknowledge the effects on relationship between streamflow and sediment  
8 load by soil conservation measures and ecological restoration, and more sustainable  
9 measures should be considered to keep soil in site while not significantly affecting  
10 streamflow. It is necessary to further research in relationship of streamflow and sediment  
11 load for the complexity nature on the regional scale.

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**Table 1.** Description of the seven catchments in the middle reaches of Yellow River, China.

Catchment	Controlling area (km <sup>2</sup> )	Mean annual precipitation (mm)	Mean annual streamflow (10 <sup>8</sup> m <sup>3</sup> )	Mean annual sediment load (10 <sup>8</sup> t)	Vegetation coverage (%)	Datum Records	Landform feature
Kuye	8645	384.6	5.8	0.91	6.5	1956-2005	Transition zone from sandy area to loess hilly-gully area
Tuwei	3253	403.0	3.4	0.18	9.8	1956-2005	
Jialu <sup>a</sup>	1121	412.0	0.6	0.13	3.3	1957-2005	
Qingjian	3468	477.7	1.4	0.40	3.6	1955-2005	Loess hilly-gully area
Yanhe	5891	514.0	2.1	0.46	9.2	1956-2005	
Yunyan	1662	541.0	0.3	0.03	54.7	1966-2005	Rocky mountain area
Shiwang	2141	561.0	0.7	0.02	66.5	1959-2005	

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<sup>a</sup>, The data of 1968 is missing.

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3**Table 2.** Cumulative area of soil conservation measures for each of catchments from 1950s to 1990s<sup>a</sup>.

Catchment	Year	Terrace (km <sup>2</sup> )	Afforestation (km <sup>2</sup> )	Pasture (km <sup>2</sup> )	Sediment trapping dam <sup>b</sup> (km <sup>2</sup> )	Area affected (%)
Kuye	1959	4.5	26.8	22.3	0.3	0.6
	1969	32.9	97.3	51.5	2.4	2.1
	1979	65.6	415.0	109.9	7.5	6.9
	1989	67.0	1004.3	353.1	12.1	16.6
	1996	99.1	1184.2	379.8	19.1	19.5
Tuwei	1959	1.0	25.4	1.4	0.2	0.9
	1969	10.8	77.7	6.1	1.7	2.9
	1979	31.3	174.7	16.1	7.1	7.0
	1989	45.5	754.5	28.8	11.1	25.8
	1996	66.5	1021.6	37.4	15.5	35.1
Jialu	1959	4.3	9.2	2.3	0.8	1.5
	1969	27.3	41.7	1.7	4.1	6.7
	1979	67.1	97.5	10.2	9.7	16.5
	1989	104.3	293.9	12.8	12.9	37.8
	1996	141.4	295.3	15.5	16.3	41.8
Qingjian	1959	6.9	13.1	0.2	1.7	0.6
	1969	41.9	46.8	2.8	11.0	3.0
	1979	92.9	110.9	6.1	31.7	7.0
	1989	145.6	596.5	25.7	46.5	23.5
	1996	161.6	652.9	27.3	46.6	25.6
Yanhe	1959	4.1	41.3	0.3	4.6	0.9
	1969	47.2	161.3	3.7	15.8	3.9
	1979	97.5	286.9	17.5	28.7	7.3
	1989	174.3	840.7	145.2	37.8	20.3
	1996	275.6	1100.2	259.9	41.7	28.5
Yunyan	1959	0.9	9.2	0.1	0.5	0.6
	1969	13.7	33.3	0.3	2.0	3.0
	1979	29.1	78.0	2.0	3.1	6.7
	1989	56.0	245.6	25.3	4.0	19.9
	1996	83.7	371.9	51.4	4.7	30.8
Shiwang	1959	4.6	1.2	0.6	0.1	0.3
	1969	16.9	30.7	1.6	0.5	2.3
	1979	38.7	67.9	3.0	1.0	5.2
	1989	59.1	150.7	10.5	1.1	10.3
	1996	73.8	233.1	12.8	1.6	15.0

4 <sup>a</sup> Referred to Ran *et al.* (2000).5 <sup>b</sup> This column represents the impounded surface area of sediment-trapping dams when full.

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**Table 3.** Trends of the annual streamflow and change points by Mann-Kendall and Pettitt test

Catchment <sup>a</sup>	Annual streamflow		Slope ( $\theta$ ) <sup>b</sup> (m <sup>3</sup> .km <sup>-2</sup> .mm <sup>-1</sup> .a <sup>-1</sup> )	Change point	
	Test Z	Significance		Year	Significance
Kuye <sup>T</sup>	-5.59	***	-3.671	1981	***
Tuwei <sup>T</sup>	-4.73	***	-2.871	1983	***
Jialu <sup>T</sup>	-7.24	***	-3.613	1982	***
Qingjian <sup>L</sup>	0.13	<i>ns</i>	0.054	—	—
Yanhe <sup>L</sup>	-0.47	<i>ns</i>	-0.071	—	—
Yunyan <sup>R</sup>	-2.53	*	-0.346	1995	***
Shiwang <sup>R</sup>	-4.13	***	-0.994	1988	***

<sup>a</sup> The superscripts in this column mean the locations of the study catchments. T means the transition zone from the sandy area to the loess hilly-gully area; L, the loess hilly-gully area; and R, the rocky mountain area. Some of following tables have the same marks.

<sup>b</sup> The unit is essentially dimensionless and the value in the column means the change rate of the runoff coefficient in catchment.

Symbols “\*”, “\*\*” and “\*\*\*” indicate significance levels of 0.05, 0.01, and 0.001, respectively.

*ns* indicates that significance level exceeds 0.05.

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**Table 4.** The relative changes in high, median, and low flow regimes in period 2 and 3 compared to the period 1 for the seven catchments.

Catchment <sup>a</sup>	Kuye <sup>T</sup>		Tuwei <sup>T</sup>		Jialu <sup>T</sup>		Qingjian <sup>lb</sup>		Yanhe <sup>lb</sup>		Yunyan <sup>R</sup>		Shiwang <sup>R</sup>	
	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3
$\Delta Q_5(\%)$	-35.8	-76.0	-43.7	-59.2	-47.4	-82.3	-6.8	-27.3	-11.0	-28.0	-38.8	-51.6	-46.2	-40.6
$\Delta Q_{50}(\%)$	-43.6	-65.7	-23.3	-40.3	-42.3	-69.2	13.8	-15.8	13.0	-17.3	-28.4	-44.2	-37.8	-52.3
$\Delta Q_{95}(\%)$	-96.1	-64.9	-16.2	-27.0	-37.3	-80.1	-63.9	23.0	42.4	1.0	-0.1	-46.0	-23.2	-54.8

<sup>a</sup> The meaning of the superscripts in this row is the same as those in Table 3.  
<sup>b</sup> The change point years for Qingjian and Yanhe catchments are given both in 1980 and 1999, referred to other catchments.

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**Table 5.** Trends of the annual sediment load and change points by Mann-Kendall and Pettitt test

Catchment <sup>a</sup>	Annual sediment load		Sen's slope ( $\beta$ ) (t.km <sup>-2</sup> .mm <sup>-1</sup> .a <sup>-1</sup> )	Change point	
	Test Z	Significance		Year <sup>b</sup>	Significance
Kuye <sup>T</sup>	-3.75	***	-0.552	1979 (1981)	***
Tuwei <sup>T</sup>	-4.38	***	-0.298	1978 (1983)	***
Jialu <sup>T</sup>	-4.85	***	-0.814	1977 (1982)	***
Qingjian <sup>L</sup>	-1.32	<i>ns</i>	-0.194	—	—
Yanhe <sup>L</sup>	-1.86	<i>ns</i>	-0.150	—	—
Yunyan <sup>R</sup>	-2.50	*	-0.053	1982 (1995)	*
Shiwang <sup>R</sup>	-5.45	***	-0.055	1982 (1988)	***

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<sup>a</sup> The meaning of the superscripts in this column is the same as that in Table 3.

<sup>b</sup> The years in bracket in the column mean the change points for the annual streamflow in the catchments.

Symbols "*\**", "*\*\**" and "*\*\*\**" indicate significance levels of 0.05, 0.01, and 0.001;

*ns* indicates that significance level exceeds 0.05.

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**Table 6.** The relative changes in high (5%), median (50%), and low (95%) of sediment load regimes in the P2 and P3 for the seven catchments, as compared to the P1.

Catchment <sup>a</sup>	Kuye <sup>T</sup>		Tuwei <sup>T</sup>		Jialu <sup>T</sup>		Qingjian <sup>lb</sup>		Yanhe <sup>lb</sup>		Yunyan <sup>R</sup>		Shiwang <sup>R</sup>	
	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3
$\Delta S_5(\%)$	-45.0	-93.1	-59.2	-90.8	-63.9	-97.2	-7.1	-47.3	-32.5	-49.0	-40.0	-63.3	-77.8	-93.5
$\Delta S_{50}(\%)$	-52.6	-89.4	-36.0	-76.3	-91.9	-100	-17.0	-100	-100	-100	—	—	—	—
$\Delta S_{95}(\%)$	-28.3	-100	-38.6	-43.6	—	—	—	—	—	—	—	—	—	—

<sup>a</sup> The mean of the superscripts in this row is the same with Table 3.

<sup>b</sup>, the change point years are given in 1977 and 1999 both for Qingjian and Yanhe catchments. P1,P2 and P3 have the same meaning as that in Table 4.



1 **Table 7** Reduction of the linear regression coefficients for the monthly sediment load and  
 2 streamflow in the catchments (%).

Catchment <sup>a</sup>	(P2 – P1)/P1	(P3 – P1)/P1
Kuye <sup>T</sup>	-25.8	-73.5
Tuwei <sup>T</sup>	-26.9	-98.7
Jialu <sup>T</sup>	-40.9	-77.5
Qingjian <sup>L</sup>	-19.9	2.7
Yanhe <sup>L</sup>	-8.1	-19.3
Yunyan <sup>R</sup>	-7.6	-23.8
Shiwang <sup>R</sup>	-28.5	-97.8
Average	<b>-22.5</b>	<b>-55.4</b>

3 <sup>a</sup> The superscripts in this column have the same meaning as that in Table 3.

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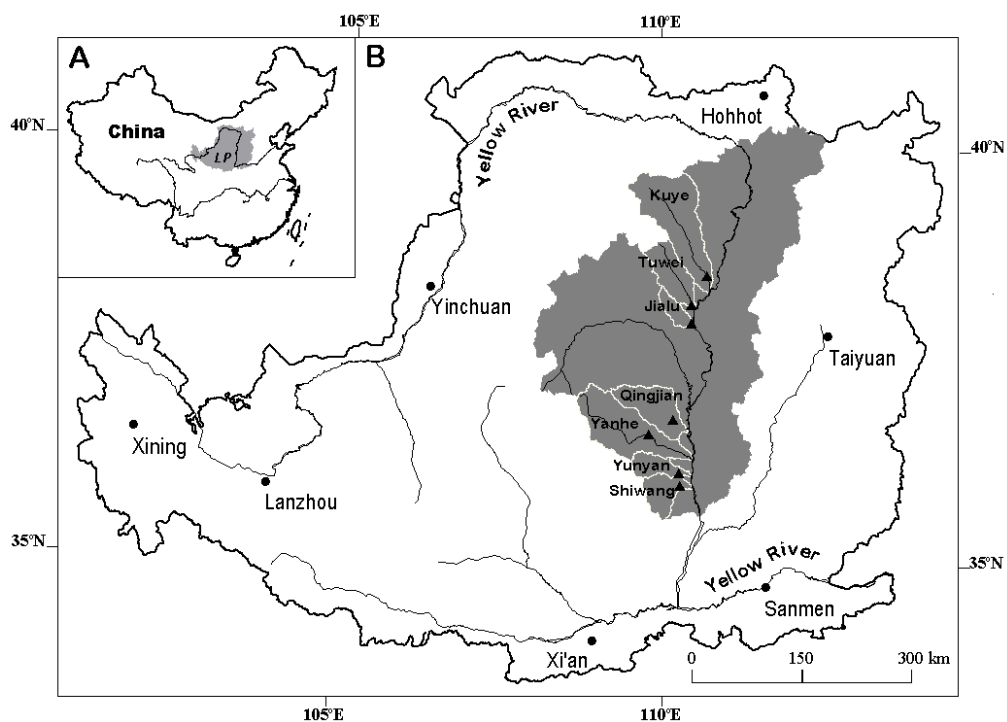
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**Table 8.** Comparison of the standardized streamflow volumes as the catchments reaches their scour and silting balances in the three periods.

Cachment <sup>a</sup>	P1	P2	P3
Kuye <sup>T</sup>	118.3	68.5	28.3
Tuwei <sup>T</sup>	245.5	181.5	-
Jialu <sup>T</sup>	113.3	61.4	16.8
Qingjian <sup>L</sup>	44.2	56.3	66.0
Yanhe <sup>L</sup>	40.1	51.6	39.3
Yunyan <sup>R</sup>	25.8	31.2	19.5
Shiwang <sup>R</sup>	-	27.7	-

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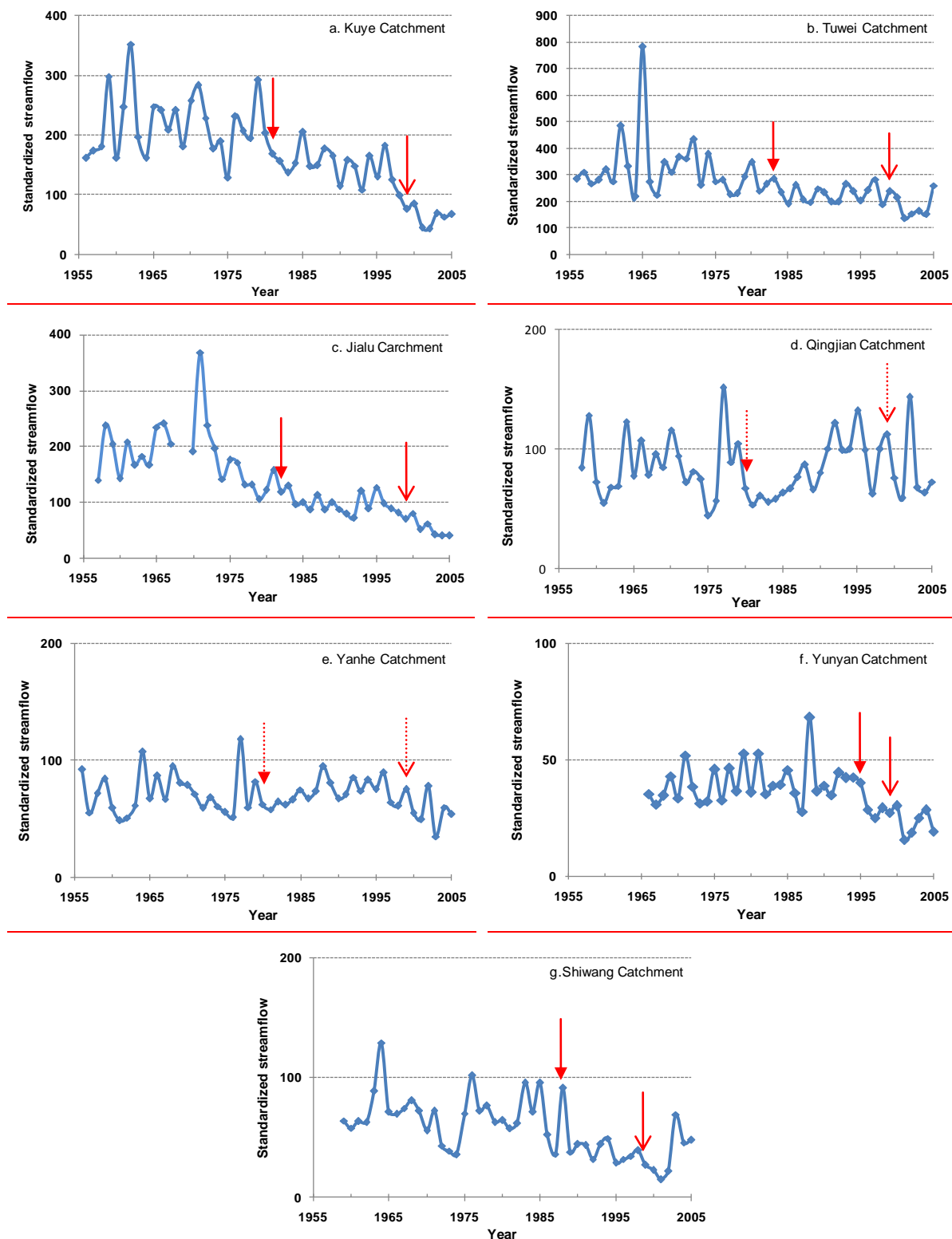
<sup>a</sup> The superscripts in this column have the same meaning as that in Table 3.



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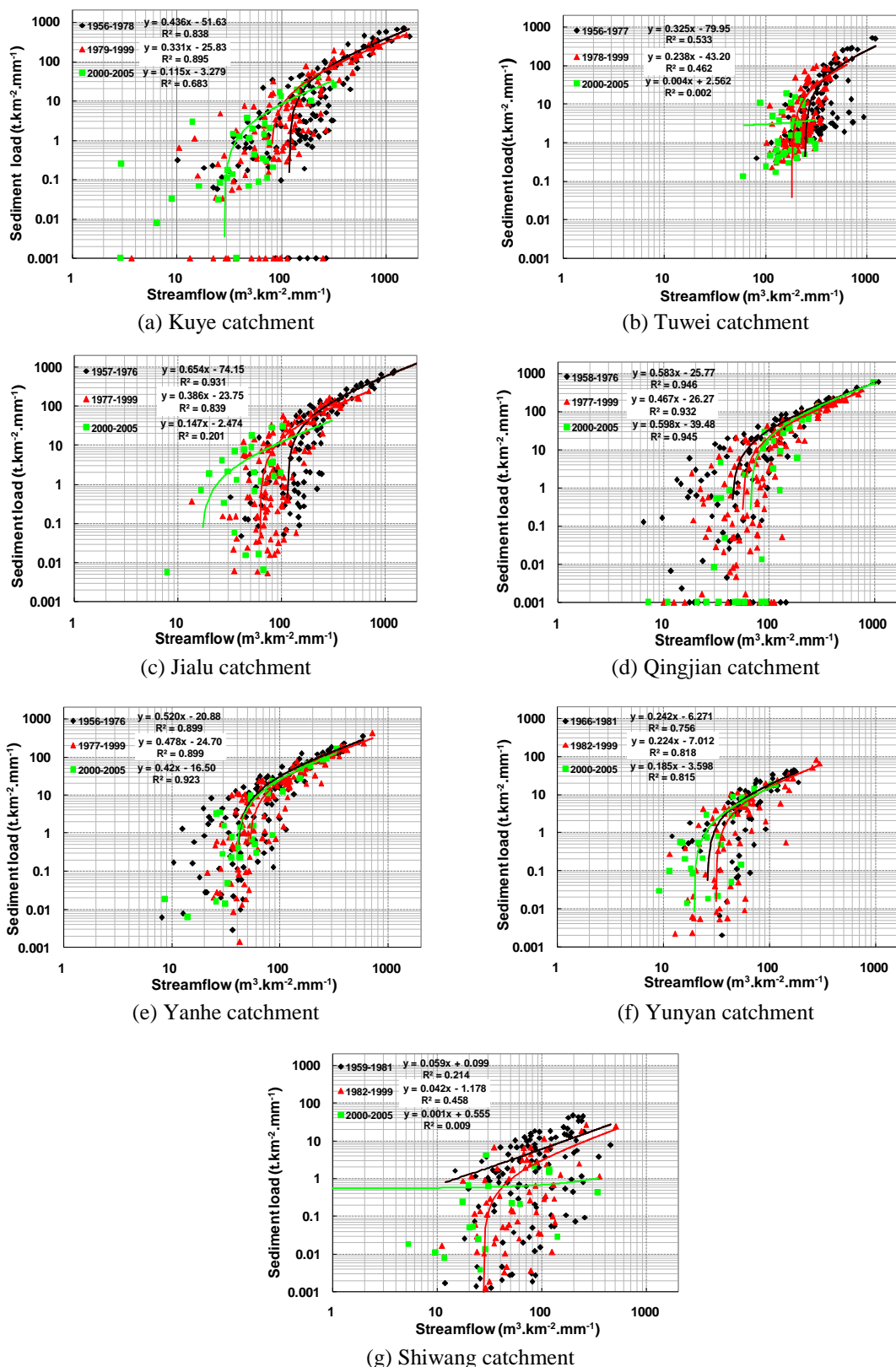
**Fig. 1. (A)** Location of the Loess Plateau (gray shading) in the middle reaches of the Yellow River, China. **(B)** location of the CSHC (gray shading) on the Loess Plateau and study catchments (marked by their names and delineated by the white lines). The triangles indicate the hydrological gauge stations in the catchments.

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2 **Fig. 2.** Standardized annual streamflow with unit  $m^3.km^{-2}.mm^{-1}$  in seven catchments. Change  
 3 points detected with Pettitt test were marked with 1<sup>st</sup> solid red arrow in plots (a), (b) and (c), three  
 4 transition zone catchments, and plot (f) and (g), two rocky mountain catchments. The 2<sup>nd</sup> red  
 5 arrows in plots (a-c) and (f-g) mean the year 1999. Change points were given in plot (d) and (e),  
 6 two loess hilly gully catchments, see Table 3.

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1 **Fig. 3** The scattered distributions and simple linear regressions for monthly standardized  
 2 streamflow and standardized sediment load from May to October in three periods in seven  
 3 catchments. Streamflow is with unit of  $m^3.km^{-2}.mm^{-1}$ , and sediment load,  $t.km^{-2}.mm^{-1}$ . It is log  
 4 transition both in X and Y-axis. Plots (a), (b) and (c) represent the scattered distribution for the

- 1 three transition zone catchments; plots **(d)** and **(e)**, for the two loess hilly-gully catchments; and
- 2 plots **(f)** and **(g)**, for the two rocky mountain catchments.
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