Hydrol. Earth Syst. Sci. Discuss., 9, 5487–5514, 2012
www.hydrol-earth-syst-sci-discuss.net/9/5487/2012/
doi:10.5194/hessd-9-5487-2012

Hydrology and
Earth System
Sciences
Discussions

Trends of streamflow, sediment load and their dynamic relations for the catchments in the middle reaches of the Yellow River in the past five decades

Z. L. Gao[1,2], Y. L. Fu[1], Y. H. Li[1,2], J. X. Liu[1,2], N. Chen[1], and X. P. Zhang[1,2]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling, Shaanxi, 712100, China
[2]Institute of Soil and Water Conservation, Institute of Soil and Water Conservation, CAS & MWR, Yangling, Shaanxi, 712100, China

Received: 29 March 2012 – Accepted: 13 April 2012 – Published: 24 April 2012

Correspondence to: Z. L. Gao (gzl@ms.iswc.ac.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

To control severe soil erosion on the Loess Plateau, China, a great number of soil conservation measures have been adopted since 1950s and subsequently, the “Grain for Green” project has been implemented from 1999. The measures and the project result in a large scale land use/cover change (LUCC). Understanding the impacts of the measures and the project on streamflow, sediment load and their dynamic relation is essential as the three elements are closely related to the sustainable catchment management strategy on the Loess Plateau. The data for seven selected catchments in the middle reaches of the Yellow River were used and standardized with precipitation and the controlling area for analysis. Nonparametric Mann-Kendall test and Pettitt test were employed to detect trends and change points of the annual streamflow and annual sediment load. Simple linear regressions for the monthly streamflow and sediment load from May to October were made to express their dynamic relation. Based on the change point identification and the time when the project began to implement on the Loess Plateau, the whole time for the data records was divided into three periods to compare the change extents in streamflow, sediment load and their dynamic relation between catchments.

Results show that there are three types of responses in streamflow, sediment load, and their dynamic relations for the seven catchments. The effects of the LUCC on streamflow, sediment load, and their dynamic relation are greatest in the three transition zone catchments with the two rocky mountain catchments followed. The effects are much weaker in the two loess hilly-gully catchments. In general, the change extents for sediment load are much greater than those for streamflow, which results in the increasingly weakening trends of statistical significance for the dynamic relation between the periods.

1 Introduction

The Loess Plateau of 620 000 km^2 is located in the middle reaches of the Yellow River (750 000 km^2). It is characterized with heavily dissected landscape and severe soil loss resulted from wind-deposited loess soils, sparse vegetation, intense rainfall, and long agricultural history. To control the severe soil erosion, a number of soil conservation measures have been adopted on the Loess Plateau since the 1950s (Ye et al., 1994; Zhang et al., 1998; Ran et al., 2000). The consequent land use and land cover changes dramatically altered hydrological regimes and significantly reduced sediment load in the Yellow River (Zhu, 1960; Liu and Zhong, 1978; Ran et al., 2000; Zhang et al., 2008; Rustomji et al., 2008). However, it is not very clear how the soil conservation measures affect their dynamic relations in the catchment. Furthermore, the “Grain for Green” project has been widely implemented from 1999. It is important to fully understand the impacts of soil conservation measures and vegetation restoration on streamflow, sediment load, and runoff-sediment behaviors in the region.

It is well known that afforestation and other measures can alter catchment’s water balance by increasing rainfall reception and evapotranspiration (Zhang et al., 2001; Brown et al., 2005). Soil erosion and sediment transport are therefore decreased through decreased surface runoff (Colman, 1953; Morgan, 1986; Sahin and Hall, 1996; Castillo et al., 1997; Quinton et al., 1997). Huang and Zhang (2004), Mu et al. (2007), and Zhang et al. (2008) found that changes in streamflow tended to be relatively uniform across the flow spectrum with typical reductions of 30–60 % in the catchments in the region due to soil conservation measures. A great number of researches showed that sediment load in the catchments on the Loess Plateau tended to have a significantly negative trend (Wang and Wu, 1993; Ye, 1994; Yu, 1997; Zhang et al., 1998; Wang and Fan, 2002; Yao et al., 2005). Runoff-sediment behaviors were also believed to change because of the mechanisms of afforestation and check dams. Xu (2002) and Liao et al. (2008) showed that the frequency of high concentration flow was decreased due to the implementation of soil conservation measures in the region. While the relation between streamflow and sediment load did not change essentially in the research of Pan et al. (1999) at a regional scale and even Zheng and Cai (2007) in the small paired catchments. Rustomji et al. (2008) also showed that soil conservation measures seemly did not significantly change the sediment rating curves in two years with the similar precipitation in two catchments on the Loess Plateau.

Above studies indicate that land use/cover changes (LUCC) resulted from soil conservation measures can affect hydrological regimes and in turn, sediment transport processes. But the results are not consistent with the change of dynamic relation between streamflow and sediment load, probably due to different research scales, mixed natures of historic soil conservation measures, spatiotemporal distribution characteristics of streamflow and sediment load on the Loess Plateau. Understanding the changes of streamflow and sediment load, and consequently their dynamic relation in the catchments on the Loess Plateau can provide an integrated estimate for the effects of soil conservation measures on hydrology and sediment transportation. Therefore, the specific objectives of this study were to (1) examine the trends and change points of annual streamflow and annual sediment load over the last 50 yr in seven selected catchments on the Loess Plateau; (2) find the changes in the streamflow and sediment load represented by monthly flow/sediment duration curves; and (3) investigate the changes of the relation between streamflow and sediment load in different periods in the catchments.

2 Study area

The 1.13×10^5 km^2 coarse sand hilly catchments (CSHC) on the Loess Plateau is recognized as the main source of coarse sediment (> 0.1 mm) on downstream bed (Fig. 1). Average annual precipitation in the CSHC is 456 mm varying from more than 600 mm in the southeast to less than 300 mm in the northwest. About 78 % of annual precipitation occurs from May to October. The northwestern part of the CSHC is considerably flat and the southeastern part is characterized by a heavily dissected landscape with gully densities ranging from 2 to 8 km km^{-2} (Chen et al., 1988; McVicar et al., 2007). The wind-deposited loess soils developed during Quaternary period cover the study area with a thickness of 50–200 m. Coarse sandy soils are common in the northwest and finer clay-rich soils occur in the southeast.

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

The areas for historic soil conservation measures in the seven catchments are given in Table 2, which are collected through census (Ran et al., 2000). The areas of terraces, afforestation, pasture land, and sediment-trapping dams all increased from 1959 to 1996. The rates of increase were greatest during 1970s and 1980s. The vegetation cover, represented by NDVI, was found to have an increasing trend at $P < 0.05$ significance level on the Loess Plateau in last 20 yr due to the "Grain for Green" project implementation (Xin et al., 2007; Sun et al., 2011).

3 Data and methods

3.1 Data description

Monthly streamflow and sediment load data in the seven catchments were obtained from the Water Resources Committee of the Yellow River Conservancy Commission of China (Table 1). Monthly precipitation data were obtained from the State Meteorology Bureau of China. Monthly precipitation data are spatially interpolated using ordinary Kriging method (Wan et al., 2011). An area-weighted method is used to compute the monthly precipitation in each catchment. Monthly streamflow, sediment load and precipitation data are then accumulated to annual totals. To reduce the effects of precipitation and drainage area on the analysis of the two elements between catchments, the volumes of annual/monthly streamflow and sediment load are standardized by controlling area and the precipitation in corresponding time. So a unit for streamflow is "$\mathrm{m^3\,km^{-2}\,mm^{-1}}$" and for sediment load, "$\mathrm{t\,km^{-2}\,mm^{-1}}$", which actually signify streamflow or sediment generation capability per unit area per unit precipitation in each catchments.

3.2 Trend test and change point analysis

3.2.1 Mann-Kendall Test

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

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

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

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

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:

$$E(S) = 0$$

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

where q is the number of tied groups and t_p is the number of data values in the pth group.

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

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

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):

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

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

3.2.2 Serial correlation test

Serial correlation has the effect of on the 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 the Mann-Kendall test. The lag 1 serial correlation coefficient, r_1, is calculated to detect the autocorrelation of the data. The lag-1 autocorrelation is the correlation between x_i and x_{i+1}. It has the formula:

$$r_1 = \frac{\sum_{i=1}^{N-1} (x_i - \bar{x})(x_{i+1} - \bar{x})}{\sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{6}$$

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 Guassian distribution (WMO, 1966):

$$r_k(95\,\%) = \frac{-1 \pm 1.96\sqrt{N-k-1}}{N-k} \tag{7}$$

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

The critical values of 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 the calculated lag-1 serial correlation coefficient, 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 changes in hydrological regimes for streamflow

Standardized annual streamflow in the five catchments except the two loess hilly-gully catchments presented negative trends at a statistically significance level by Mann-Kendall test. The rate of streamflow change was $-3.39\,\mathrm{m^3\,km^{-2}\,mm^{-1}\,a^{-1}}$ in the three transition zone catchments, but only $-0.67\,\mathrm{m^3\,km^{-2}\,mm^{-1}\,a^{-1}}$ in the two rocky mountain catchments. The 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. The change rate in Qinjian catchment presented a slightly increasing trend, but in Yanhe catchment, a slightly decreasing trend, both of which were statistically insignificant (Table 3).

The annual streamflow in the five catchments had statistically significant change points, as shown in 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. Clearly, years for the former were all earlier than those for the latter. The reason for such an occurrence is probably related to the time when the cumulative area of soil conservation measures in the catchments reached about 15 %. Result from Ran et al. (2000) indicates that such a percentage of soil conservation measures can significantly affect hydrological recycling 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 for the sequential streamflow data is divided into three periods: period 1 (pre-change point year period, abbreviated to P1), period 2 (post-change period from the 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 the relative changes of the streamflow in high (5 %), median (50 %) and low (95 %) percentiles of time in the periods 2 and 3 are listed in Table 4, as compared to the period 1.

From Table 4, the relative changes of streamflow were negative except for the two loess hilly-gully catchments, i.e. Qinjian and Yanhe catchments. The change extents, whenever in the period 2 and period 3, were higher in the three transition zone catchments than those in the two rocky mountain catchments.

The change extents of streamflow in the transition zone catchments were not only greater in the period 3 than those in the period 2, but also much greater than those in the rocky mountain catchments in the period 3. The average relative changes for the three transition zone catchments in the period 3 reached 72.5 %, 58.4 %, and 57.3 % at the high, median, and low percentiles of time, respectively. Moreover, the average relative changes for the two rocky mountain catchments in the period 3 were 46.1 %, 48.3 %, and 50.4 % at the same percentiles, respectively. That means that the implementation of soil conservation measures had greater effects on the transition zone catchments than the rocky mountain catchments, especially in the period 3 when the “Grain for Green” project was implemented.

The change extents were much weaker for the two loess hilly-gully catchments, i.e. Qinjian and Yanhe catcments. The result is consistent with the trend detection for the five catchments.

4.2 Trends, change points and relative changes for sediment load

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

The change points of sediment load were also earlier in the three transition zone catchments, from 1977 to 1979. The change points in the two rocky mountain catchments were later, both in 1982 (Table 5). Compared to Table 3, the change points of the annual sediment load in the five catchments were close to those of the annual streamflow except Yunyan catchment, which implies that the effects of controlling erosion and sediment yield in these catchments are achieved through the surface runoff reduction by soil conservation measures. To investigate the relative changes in sediment load in the seven catchments, three periods are divided for in sediment load data based on the same period division criterion as for streamflow (Table 6).

Table 6 shows that compared to period 1, all the relative changes in the seven catchments are negative at the high, median, and low percentiles of sediment transport regime in the two latter periods. The increasing number of zero sediment load days in catchments is observed in the catchments including the two loess hilly-gully catchments.

For the three transition zone catchments, the average relative changes at the high (5 %), median (50 %) and low (95 %) sediment load in the period 2 were 56.0 %, 60.2 % and 33.5 % and in the period 3, 93.7 %, 88.6 % and 71.8 %, respectively. There were considerable differences in the relative change between the two periods. For the two rocky mountain catchments, the average relative change at high sediment load was 58.9 % in the period 2 and 78.4 % in the period 3. The result indicates significant effects of the soil conservation measures and "Grain for Green" project on sediment transportation in the study catchments. However, the effect of "Grain for Green" project implementation is much greater than that of soil conservation measures due to the continuity in the implementation process.

Compared to the streamflow, the change extents in sediment load, whatever the three flow/sediment load regimes and catchments are, are observed much greater.

4.3 The dynamic relation between streamflow and sediment load in the catchments

The change points of sediment load in the seven catchments are used to analyze the dynamic relation of streamflow to sediment load. Figure 2 is a set of scatter diagrams illustrating relations of the monthly sediment load to the monthly streamflow in the three periods in the seven catchments with simple linear regression equations presented simultaneously. The monthly data of sediment load and streamflow used in this section are the values over the time from May to October.

Some equations in Fig. 2b, c, g, have poor correlative coefficients, which indicate that the sediment transport processes in the periods were largely influenced by human activities like soil and water conservation measures and the "Grain for Green" project implementation.

The domain of the scattered distributions of the monthly sediment load against the monthly streamflow in the three transition zone catchments is up to $\{1400, 1000\}$, whereas in the two rocky mountain catchments, only $\{600, 100\}$. Apparently, the former is much wider than the latter. The domain of the scattered distribution in the two loess hilly-gully catchments lies in the middle.

The regression coefficients can be considered as "sediment generation coefficients" because they may indicate the sediment generation capacity in the catchments. Figure 2 shows that the linear regression coefficients, in general, are much higher in the transition zone catchments and the loess hilly-gully catchments than those in the rocky mountain catchments. The average coefficients in periods 1, 2 and 3 are 0.4723, 0.3164 and 0.0891 in the three transition zone catchments and 0.5519, 0.4728 and 0.5093 in the two loess hilly-gully catchments, while they are only 0.1513, 0.1336 and 0.0932 in the two rocky mountain catchments. This indicates that with per unit of streamflow, the catchments located in the transition zone and loess hilly-gully area had a stronger capacity to generate and transport sediment than the catchments in the rocky mountain area. The reason is considerably related to the high vegetation cover in the rocky mountain area catchments, as shown in Table 1.

Both the adoption of soil conservation measures from the 1970s to 1980s and the implementation of "Grain for Green" project after 1999 made the sediment generation capacity in the catchments to be increasingly negative trends period by period, except the two loess hilly-gully catchments (Table 7). Compared to the period 1, the average reduction rate of linear regression coefficients in the period 2 is 31.2 % in the transition zone catchments and only 18.0 % in the rocky mountain catchments, but in the period

3, it is up to 83.2 % and 60.8 %, correspondingly. However, the negative trend is not evident in the loess hilly-gully catchments. The average reduction in the period 2 in all seven catchments is 22.4 % and in the period 3, 63.4 % (Table 7).

In this study, the absolute value of a constant in the linear regression equation for each of the catchments implies the sediment storage situation in a given period. In the period 1, much more sediment was stored in the three transition zone catchments than in the two loess hilly-gully catchments and the two rocky mountain catchments (Fig. 2). Correspondingly, the average constants are 68.6, 23.3 and 6.3. Respectively. The sediment storage in the catchments showed a decreasing trend period by period except Qingjian catchment in the loess hilly-gully region. Compared to the period 1, the soil conservation measures from 1970s to 1980s made the sediment storage in the transition zone catchments and the rocky mountain catchments decreasing by 56.6 % and 34.7 % and the "Grain for Green" project implementation further decreasing by 95.8 % and 42.6 %, respectively.

From the point view of equation, the streamflow volume at which sediment load equals zero may be understood as the situation in which a given catchment reaches its scour and silting balance (Fig. 2). The standardized streamflow volume, at which the balance is needed for a catchment showed a decreasing trend with the shifted period in most of the catchments (Table 8). Especially in the three transition zone catchments, the average reduction of the streamflow volume, at which the balance needed, reached 38.0 % in the period 2 and up to 80.6 % in the period 3.

Above all, the trends of three indices, i.e. regression equation coefficient, regression equation constant and the streamflow volume at which a scour and silting balance reaches are found to be increasingly negative in most of the catchments. The decreased trends indicate that soil conservation measures and the "Grain for Green" project considerably weakened the sediment yield capacity and the dynamic relation of sediment load to streamflow in the study catchments.

In considering of the standardization of the data by annual/monthly precipitation and catchment area, the decreasing/weakening trends of streamflow, sediment load, and their dynamic relation in the catchments were probably related to the characteristics of soil conservation measures adopted after 1950s. One was the total area controlled by soil conservation measures, by which the LUCC significantly affected hydrological recycling in a catchment. The other was the structure of soil conservation measures. It was the differences of landform and vegetation coverage that resulted in the intrinsic difference in the change extent between catchments. The responses of streamflow and sediment load to the LUCC in Qingjian and Yanhe catchments are different from those in other catchments. The results agree with those from Dai and Yan (2002), Zhang et al. (2008), probably due to other kinds of human activities which could aggravate soil erosion and increase sediment transportation.

5 Summary

The impacts of soil conservation measures and the subsequent "Grain for Green" project on the standard streamflow, standard sediment load, and their dynamic relation were examined for the seven catchments in the middle reaches of the Yellow River, China. The responses showed a big variety but generally three types could be identified based on the spatial distribution of the catchments. Both the annual streamflow and annual sediment load were tested with significant negative trends and change points in the three transition zone catchments and two rocky mountain catchments. In most of the cases, the decreasing change extents of streamflow, sediment load in the three sandy transition catchments were greater than those in the two rocky mountain catchments. The change points detected in the transition zone catchments were earlier than those in the rocky mountain catchments. The change extents with the shifted periods in sediment load were much greater than those in streamflow, especially in the three transition zone catchments. The non-linearity of runoff-sediment production processes resulted in a statistically significant weakening trend in their dynamic relation in catchments. The implementation of soil conservation measures from 1970s to 1980s reduced the sediment generation capability in catchments by 22.4 % and

the subsequent “Grain for Green” project after 1999 further reduced it by 63.4 %. The effects of the LUCC on the elements were much weaker in the two loess hilly-gully catchments probably due to the other intensive human activities.

Acknowledgements. The work was supported by the National Natural Science Foundation of China (Grant No. 41101265) and the National Basic Research Program of China (973 Program) (2007CB407203).

References

Bi, H. X., Liu, B., Wu, J., Yun, L., Chen, Z. H., and Cui, Z. W.: Effects of precipitation and landuse on runoff during the past 50 yr in a typical watershed in Loess Plateau, China, Int. J. Sediment Res., 24(3), 352–364, 2009.

Brown, A. E., Zhang, L., McMahon, A. W., and Vertessy, R. A.: A review of paired catchment studies foe determing changes in water yield resulting from alterations in vegetation, J. Hydrol., 310(1–4), 28–61, 2005.

Castillo, V. M., Martinez-Mena, M., and Albaladejo, J.: Runoff and soil loss response to vegetation removal in a semiarid environment, Soil Sci. Soc. Am. J., 61, 1116–1121, 1997.

Chen, Y. Z., Jing, K., and Cai, Q. G.: Modern soil erosion and its controlling on the Loess Plateau, Science Press, Beijing, 1988 (in Chinese).

Colman, E. A. (Ed.): Vegetation and watershed management, The Ronald press company, New York, 1953.

Dai, M. Y. and Yan, L.: Analysis of Yanhe streamflow and sediment load, in: Researches on streamflow and sediment load in Yellow River, Volume I, edited by: Wang, G. and Fan, Z., Yellow River Water Conservancy Press, Zhengzhou, 623–643, 2002 (in Chinese).

Hamed, K. H. and Rao, A. R.: A modified Mann-Kendall trend test for autocorrelated data, J. Hydrol., 204, 182–196, 1998.

Hirsch, R. M., Slack, J. R., and Smith, R. A.: Techniques of trend analysis for monthly water quality data, Water Resour. Res., 18, 107–121, 1982.

Huang, M. B. and Zhang, L.: Hydrological responses to conservation practices in a catchment of the Loess Plateau, China, Hydrol. Process., 18, 1885–1898, 2004.

Kendall, M. G.: Rank Correlation Measures, Charles Griffin, London, 1975.

Liao, J. H., Xu, J. X., and Yang, Y. H.: Study of the spatial differentiation of hyperconcentrated flows frequency in the Loess Plateau, Adv. Water Sci., 19(2), 160–170, 2008 (in Chinese).

Liu, C. M. and Zhong, J. R.: The effect of forest on stream flow in the Loess Plateau, Acta Geogr. Sinica, 33, 112–126, 1978 (in Chinese).

Mann, H. B.: Non-parametric tests against trend, Econometrica, 13, 245–259, 1945.

McVicar, T. R., Li, L. T., Van Niel, T. G., Zhang, L., Li, R., Yang, Q. K., Zhang, X. P., Mu, X. M., Wen, Z. M., Liu, W. Z., Zhao, Y. A., Liu, Z. H., and Gao, P.: Developing a decision support tool for China's re-vegetation program: simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau, Forest Ecol. Manag., 251, 65–81, doi:10.1016/j.foreco.2007.06.025, 2007.

Morgan, R. P. C. (Ed.): Soil erosion and conservation, Longman Scientific and Technology, Harlow, Essex, England, 21–27/45–47, 1986.

Mu, X. M., Zhang, L., McVicar, T. R., Chille, B. S., and Gao, P.: Estimating the impact of conservation measures on stream-flow regime in catchments of the Loess Plateau, China, Hydrol. Process., 21, 2124–2134, 2007.

Pan, X. D., Li, Y., and Zhang, X. H.: The influence of the comprehensive treatment to streamflow and sediment load in the Hekou-Longmen region of Yellow River, Yellow River, 21(8), 13–15, 1999 (in Chinese).

Partal, T. and Kahya, E.: Trend analysis in Turkish precipitation data, Hydrol. Process., 20, 2011–2026, 2006.

Pettitt, A.: A nonparametric approach to the change-point problem, Appl. Stat.-J. Roy. St. C, 28, 126–135, 1979.

Quinton, J. N., Edwards, G. M., and Morgan, R. P. C.: The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in South East Spain, Soil Use Manage., 13, 143–148, 1997.

Ran, D. C., Liu, L. W., and Zhao, L. Y. (Eds.): The soil conservation practices and streamflow and sediment load changes in the Hekou-Longmen region of middle reaches of Yellow River, Yellow River Water Conservancy Press, Zhengzhou, 2000 (in Chinese).

Rustomji, P., Zhang, X. P., Hairsinen, P. B., Zhang, L., and Zhao, J.: River sediment load and concentration responses to changes in hydrology and catchment management in the Loess Plateau region of China, Water Resour. Res., 44, W00A04, doi:10.1029/2007WR006656, 2008.

Sahin, V. and Hall, M. J.: The effects of afforestation and deforestation on water yields, J. Hydrol., 178(1/4), 293–309, 1996.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, J. Am. Stat. Assoc., 39, 1379–1389, 1968.

Sun, Y. P., Zhang, X. P., Xu, J. P., Ma, T. Y., and Lei, Y. N.: Temporal and spatial variation of NDVI of the water-wind erosion crisscross region in the Loess Plateau, J. Northwest Sci-Tech Univ. Agric. For. (Nat. SCI. Ed.), 40, 143–150, 2012 (in Chinese).

Wan, L., Zhang, X. P., Ma, Q., Zhang, J. J., Liu, E. J., and Xie, M. L.: Spatiotemporal Trends of Precipitation on the Loess Plateau of China, in: International Congress on Modelling and Simulation, MODSIM, Perth, Australia, 12–16 December 2011.

Wang, G. and Fan, Z. (Eds.): Researches on streamflow and sediment load in Yellow River, Volume I, Yellow River Water Conservancy Press, Zhengzhou, 623–643, 2002 (in Chinese).

Wang, Y. Z. and Wu, X. D.: The primary analysis of the relation of sediment load and climate in the up and middle reaches of the Yellow River for the past 70 yr, in: The corpus of the study on environmental evolution and the streamflow and sediment transport rules in the Yellow River, edited by: Niu, Z. X., Geology Press, Beijing, 1993 (in Chinese).

Xin, Z. B., Xu, J. X., and Zheng, W.: Response of vegetation cover change to climate change and human activities in Loess Plateau, Sci. China Ser. D, 37(11), 1504–1514, 2007 (in Chinese).

Xu, J. X.: The impacts of human activity on hyperconcentrated flow in the middle reaches of Yellow River, Sci. Geogr. Sinica, 3, 294–299, 2002 (in Chinese).

Xu, Z. X., Takeuchi, K., Ishidaira, H., and Li, J. Y.: Long-term trend analysis for precipitation in Asian Pacific FRIEND river basins, Hydrol. Process., 19(18), 3517–3532, 2005.

Yao, W. Y., Li, Z. B., and Kang, L. L.: The effects of controlling soil erosion on environment on the Loess Plateau, Science and Technology Press, Beijing, 2005 (in Chinese).

Ye, Q. C. (Ed.): Researches on environemtnal changes of the Yellow River Basin and laws of water and sediment transportation, Shandong Science and Technology Press, Jinan, 1994 (in Chinese).

Yu, Y. M.: The trend study of soil conservation measures' benefit and streamflow and sediment load in the coarse sandy hilly area in the middle reaches of the Yellow River, Yellow River Water Conservancy Press, Zhengzhou, 1997 (in Chinese).

Zhang, S. L., Li, Z., and Zhao, W. L. (Eds.): The reason and developing trend of streamflow and sediment load in the Rich and Coarse Sandy region in the Yellow River, Yellow River Water Conservancy Press, Zhengzhou, 1998 (in Chinese).

Zhang, L., Dawes, W., and Walker, G.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res., 37, 701–708, 2001.

Zhang, X. P., Zhang, L., Zhao, J., Rustomji, P., and Hairsine, P.: Responses of streamflow to changes in climate and land use/cover change in Loess Plateau, China, Water Resour. Res., 44, W00A07, doi:10.1029/2007WR006711, 2008.

Zheng, M. G. and Cai, Q. G.: Effects of vegetation and other measures for soil and water conservation on runoff-sediment realtionship in watershed scale, J. Water Conserv., 38(1), 47–53, 2007 (in Chinese).

Zhu, X. M.: The impacts of vegetation on soil loss in the Loess region. Acta Pedol. Sinica, 8(2), 110–120, 1960 (in Chinese).

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

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

Table 2. Cumulative area of soil conservation measures for each of catchments from 1950s to 1990s[a].

Catchment	Year	Terrace (km^2)	Afforestation (km^2)	Pasture (km^2)	Sediment trapping dam[b] (km^2)	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	26.6	22.3	0.3	1.5
	1969	10.8	97.3	51.5	2.4	5.0
	1979	31.3	415.0	109.9	7.5	17.3
	1989	45.5	1004.3	353.1	12.1	43.5
	1996	66.5	1184.2	379.8	19.1	50.7
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

[a] Referred to Ran et al. (2000).

[b] This column represents the impounded surface area of sediment-trapping dams when full.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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

Catchment[a]	Annual streamflow		Slope (β)	Change point	
	Test Z	Significance	($m^3\,km^{-2}\,mm^{-1}\,a^{-1}$)	Year	Significance
Kuye[T]	−5.59	***	−3.671	1981	***
Tuwei[T]	−4.73	***	−2.871	1983	***
Jialu[T]	−7.24	***	−3.613	1982	***
Qingjian[L]	0.13	*ns*	0.054	–	–
Yanhe[L]	−0.47	*ns*	−0.071	–	–
Yunyan[R]	−2.53	*	−0.346	1995	***
Shiwang[R]	−4.13	***	−0.994	1988	***

[a] 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.
Symbols “*”, “**”, and “***” indicate significance levels of 0.05, 0.01, and 0.001, respectively.
ns indicates that significance level exceeds 0.05.

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[a]	Kuye[T]		Tuwei[T]		Jialu[T]		Qingjian[L b]		Yanhe[L b]		Yunyan[R]		Shiwang[R]	
	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3
ΔQ_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
ΔQ_{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
ΔQ_{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

[a] The meaning of the superscripts in this row is the same as those in Table 3.

[b] The change point years for Qingjian and Yanhe catchments are identified both in 1980 and 1999, refereed to other catchments.

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

Catchment[a]	Annual sediment load		Sen's slope (β)	Change point	
	Test Z	Significance	($\mathrm{t\,km^{-2}\,mm^{-1}\,a^{-1}}$)	Year[b]	Significance
Kuye^{T}	−3.75	***	−0.552	1979 (1981)	***
Tuwei^{T}	−4.38	***	−0.298	1978 (1983)	***
Jialu^{T}	−4.85	***	−0.814	1977 (1982)	***
Qingjian^{L}	−1.32	*ns*	−0.194	–	–
Yanhe^{L}	−1.86	*ns*	−0.150	–	–
Yunyan^{R}	−2.50	*	−0.053	1982 (1995)	*
Shiwang^{R}	−5.45	***	−0.055	1982 (1988)	***

[a] The meaning of the superscripts in this column is the same as that in Table 3.

[b] 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.

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[a]	Kuye^T		Tuwei^T		Jialu^T		Qingjian$^{L\,b}$		Yanhe$^{L\,b}$		Yunyan^R		Shiwang^R	
	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3	P2	P3
ΔS_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
ΔS_{50} (%)	−52.6	−89.4	−36.0	−76.3	−91.9	−100	−17.0	−100	−100	−100	–	–	–	–
ΔS_{95} (%)	−28.3	−100	−38.6	−43.6	–	–	–	–	–	–	–	–	–	–

[a] The mean of the superscripts in this row is the same with Table 3.

[b] The change point years are identified in 1977 and 1999 both for Qingjian and Yanhe catchments. P1, P2 and P3 have the same meaning as that in Table 4.

Table 7. Reduction of the linear regression coefficients for the monthly sediment load and streamflow in the catchments.

Catchment*	(P2 – P1)/P1	(P3 – P1)/P1
Kuye^T	−25.8	−73.5
Tuwei^T	−26.9	−98.7
Jialu^T	−40.9	−77.5
Qingjian^L	−19.9	2.7
Yanhe^L	−8.1	−19.3
Yunyan^R	−7.6	−23.8
Shiwang^R	−28.5	−97.8
Average	−22.4	−63.4

* The superscripts in this column have the same meaning as that in Table 3.

HESSD
9, 5487–5514, 2012

Trends of streamflow, sediment load and their relations on the LP

Z. L. Gao et al.

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

Cachment*	P1	P2	P3
Kuye^T	118.3	68.5	28.3
Tuwei^T	245.5	181.5	–
Jialu^T	113.3	61.4	16.8
Qingjian^L	44.2	56.3	66.0
Yanhe^L	40.1	51.6	39.3
Yunyan^R	25.8	31.2	19.5
Shiwang^R	–	27.7	–

* The superscripts in this column have the same meaning as that in Table 3.

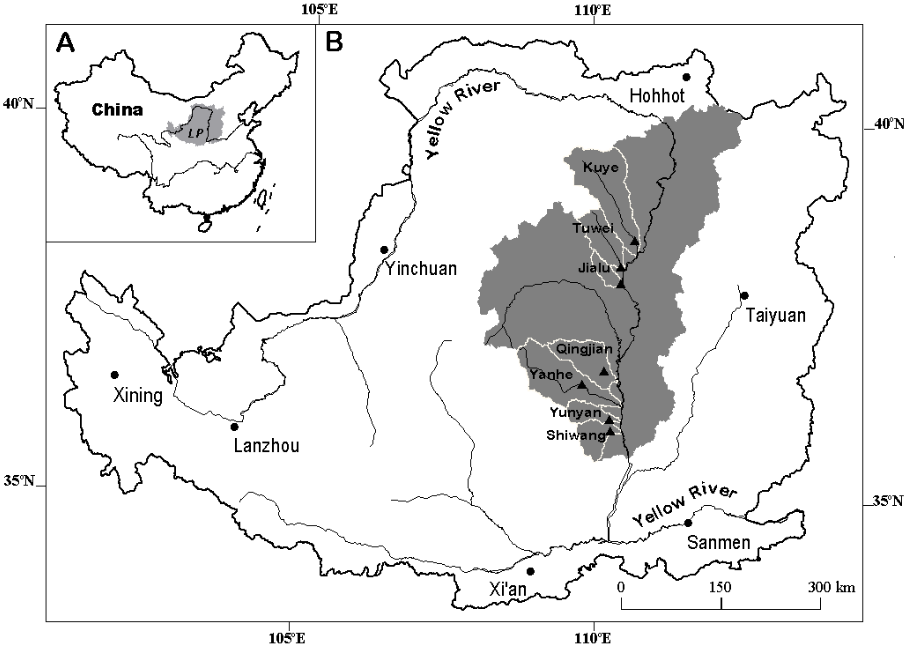

Fig. 1. (A) Location of the Loess Plateau (gray shading) in the middle reaches of the Yellow River, China. **(B)** Location of the CSHC (gray shading) on the Loess Plateau and study catchments (marked by their names and delineated by the white lines). The triangles indicate the hydrological gauge stations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

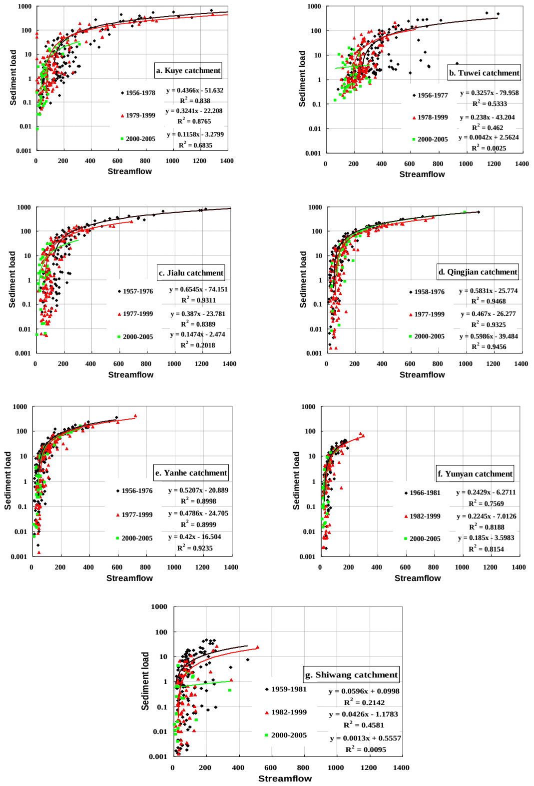

Fig. 2. The scattered distributions and simple linear regressions for the monthly sediment load and monthly streamflow from May to October in the three periods in the seven catchments. It is normal in x-axis and the log transition in y-axis. Plots **(a)**, **(b)** and **(c)** in this figure represent the scattered distribution for the three transition zone catchments; plots **(d)** and **(e)** for the two loess hilly-gully catchments; and plots **(f)** and **(g)** for the two rocky mountain catchments.