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Effects of watershed management practices on the relationships among rainfall, runoff, and sediment delivery in the hilly-gully region of the Loess Plateau in China

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ABSTRACT

The relationships among rainfall, runoff, and sediment delivery are significant in predicting soil erosion and in evaluating the benefits of watershed management practices (WMP) on the hilly-gully regions of the Loess Plateau. Hydrologic data (1987 to 2010) were analyzed for variations in precipitation, runoff, and sediment delivery at annual and event scale. These data were obtained from the Qiaozi East watershed (QE) and the Qiaozi West watershed (QW) with and without WMP, respectively. Results indicated that the runoff coefficients of the watersheds decreased significantly, although the runoff coefficient of QE was less than half of that of QW. Sediment delivery decreased more in QE than in QW mainly because of the increase in vegetation cover in both watersheds. In QE, the relationship between runoff and sediment delivery did not change significantly from 1987 to 2006, although the variation was significant from 2007 to 2010. In QW, the relationship between runoff and sediment delivery was not notably altered from 1987 to 2010. This finding suggested that vegetation practices and engineering measures on the hillslope did not strongly affect the relationship between runoff and sediment delivery in the watersheds. But the construction of check dams reduced gully erosion and the suspended sediment concentration. Hence, control practices for gully erosion significantly influenced the relationship between runoff and sediment delivery. This study suggests that a combination of hillslope and gully erosion control practices effectively reduces erosion and sediment delivery in the hilly-gully regions of the Loess Plateau.

1. Introduction

Soil erosion has induced many costly environmental problems for the society because it adversely affects crop yield and long-term soil productivity of cultivated land. It reduces topsoil and fertility of farmland (Verstraeten et al., 2002; Ward et al., 2007) and affects the delivery of eroded sediments from agricultural areas carrying nutrients, pesticides, and heavy metal contaminants to rivers and channels (e.g., Boers, 1996; De Wit and Behrendt, 1999; Verstraeten and Poesen, 2002), which can affect the quality of river water and of water in coastal areas. Sediment delivery also influences channel and floodplain morphology (e.g., Asselman and Middelkoop, 1995; De Moor et al., 2008; Ward et al., 2009), the ecological functions of floodplains (Richards et al., 2002), and sediment deposition rates in reservoirs and ponds (Verstraeten and Poesen, 2002). Because of human activities (such as farming, disafforestation, mining), soil erosion has been a serious issue in the hilly-gully region of the Loess Plateau of China, resulting in a number of environmental problems, including reservoir siltation, degradation of aquatic habitats and river water quality, and the transfer and storage of sediment-associated nutrients and contaminants in river systems, which have significant effects on the safety of the Yellow River and on economic loss.

A few intensive storms produce most of the annual runoff and sediment from the watersheds in the hilly-gully region (Cai et al., 1998; Zheng et al., 2008). To influence runoff and sediment delivery, human activities such as watershed management practices (WMP) modify land use or land cover and watershed geography. The WMP includes practices for vegetation, slope engineering, and gully erosion control; and these practices have long been implemented to conserve soil and water in the hilly-gully region. As a result, land use/coverage and channel morphology in the watersheds are changed significantly. A small watershed or catchment is a hydrologically closed and isolated area to

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become a basic management unit. Thus, the comprehensive management practices for soil erosion control have been using small watersheds as basic units to control soil and water loss in China.

Sediment production from a watershed is closely related to and affects watershed geomorphological aspects. The implementation of WMP altered the geomorphology through its impacts on soil erosion. Altered geomorphology in turn has its feedback effects on the hydrological process and sediment delivery. The construction of check dams cuts short the length and gradient of gullies and channels. A shorter gully channel possibly produces and delivers less sediments. Shorter channels are known to have less opportunity of channel erosion and of reducing the sediment transport capability (Xu et al., 2004; Boix-Fayos et al., 2007; Castillo et al., 2007). Sediments deposited behind a check dam change the local geomorphology by increasing the elevational difference and reducing soil erosion and sediment delivery. Vegetation, a major watershed management practice, increases the land coverage in watersheds, which changes the local geomorphologies in terms of surface roughness, the root systems and wormholes. All these changes in geomorphologic aspect in turn affect the hydrological process and sedimentation (Bochet et al., 1998; Gyssels and Poesen, 2003; Gyssels et al., 2005; Mohammad and Adam, 2010). Hillslope conservation practices affect the macro- and/or microgeomorphologies to produce positive impacts on reduction of runoff and sediments. For instance, terraces make a steep slope flat to reduce the slope length and the length of runoff passage. This also enhances the soil moisture condition for the benefit of vegetation growth. All these practices reduce soil erosion through changed geomorphology (Liu et al., 2013).

According to previous studies, WMP reduced runoff and sediment in the watersheds of the hilly-gully region of the Loess Plateau (Jiao et al., 2001; Hessel et al., 2003; Zhu et al., 2007; Wang et al., 2008; Bi et al., 2009; Yu et al., 2009; Yuan et al., 2010; Zhang et al., 2010). This reduction may be caused by the alteration of the process of runoff and sediment delivery by WMP (Xu, 2004; Zhang et al., 2007; Yuan et al., 2010). In some watersheds, the percentage of runoff reduction is lower than that of sediment reduction (Wang et al., 2006; Qi et al., 2010). However, these percentages are almost similar in other watersheds (Zheng et al., 2007b). The runoff coefficients of watersheds decreased with the increase in vegetation cover (Zhao et al., 2004; Wang et al., 2006; Bi et al., 2009; Zhang et al., 2009). However, Hao et al. (2004) reported that the increase in forest cover increased annual runoff. Sriwongsitanon and Taesombat (2011) also noted that the runoff coefficient increased with the increase in forest proportion during high runoff events.

With regard to the watersheds in the hilly-gully region, sediment delivery is closely related to runoff. Thus, the linear or power function has often been used to establish the relationship between these factors (Gong and Jiang, 1978; Jiang and Song, 1980; Wang et al., 1982; Wang and Zhang, 1990; Cai et al., 2004; Zheng et al., 2007a, 2008).

The relationship between runoff and sediment delivery is one of the fundamental elements determining sediment dynamics, and studies on this topic have been numerous (e.g., Muller and Forstner, 1968; Williams, 1989; Seeger et al., 2004). According to previous studies, different arguments were made for the effect of WMP on the relationship between runoff and sediment delivery at the watershed scale in the hilly-gully region on the Loess Plateau. For example, Zhao et al. (2004) and Liu et al. (2010) presented that the relationship between runoff and sediment delivery is altered due to land use/coverage change, without giving the reason. However, Zheng et al. (2007b) reported that vegetation and other slope practices did not change the relationship between runoff and sediment delivery, which had no discussion on the low runoff events.

These results are supported by calculations with a linear or power function. Although the findings fit the data, they are limited. For instance, the fitting result is unreliable if the amount of data regarding runoff and sediment delivery is reduced and the values are abnormal. Significant variations in these abnormal values enhance the residual influence of these data on the fit line and shorten the distance between the data and the fit line, thus creating distortion. Generally, these abnormal values are eliminated, but this process induces two problems: first, the fitting function is affected because the amount of samples decreases, especially given limited data; second, abnormal values may reflect special circumstances in runoff and sediment delivery and should not be eliminated unwisely. To limit interference from abnormal values, the variation in the relationship between runoff and sediment delivery should be investigated using nonparametric test methods.

To clarify the effects of WMP on the relationships among rainfall, runoff, and sediment delivery at the watershed scale in the hilly-gully region of the Loess Plateau, this study mainly aims to:

(i) investigate the variation in rainfall, runoff, and sediment at annual and event scales in watersheds using a nonparametric test method;
(ii) examine whether the relationships between runoff and sediment in similar watersheds are similar; and
(iii) explore the effect of WMP on the relationship between runoff and sediment.

2. Materials and methods

2.1. Study area

The Qiaozi East watershed (QE) and the Qiaozi West watershed (QW) are adjacent catchments within the Luoyugou watershed (LYG) that is located in Tianshui City in the Gansu Province of China (34°36′–34°37′ N., 105°42′–105°43′ E.). These watersheds are situated in the southwestern hilly-gully region of the Chinese Loess Plateau (Fig. 1). The area is influenced by dry and continental climates with an average annual precipitation of 542.5 mm. Seventy-two percent of this precipitation occurs in the period of May to September. Historically, the maximum annual precipitation was 867.7 mm in 2003, and the minimum was 342.1 mm in 1997. In this area, the mean annual temperature is 10.7 °C, with a minimum mean temperature of −2.3 °C in January and a maximum of 22.6 °C in July. The highest and lowest recorded temperatures are 38.2 °C and −19.2 °C, respectively. In the summer, intense storms erode much soil; and from 1987 to 2010, average annual sediment delivery in QE and QW measured 2004.6 and 5755.9 t km^{-2} y^{-1}, respectively.

The natural condition of QE is similar to that of QW. The main soil class is Lixisols (FAO, 2014), occupying more than 82% of the watershed area. According to soil mechanical analysis, the upper horizon is a loam texture (20.15-20.77% of clay particles, 34.99–36.88% of silt particles, and 42.35–44.86% of sandy particles). Fluvisols cover 3% of the watershed area. Table 1 shows that the significant geographic information indicates the similarity between QE and QW, especially with high gully density. Gully erosion plays an important role in the study area, accounting for over 60% of soil erosion, which is the main source of sediment delivery. An example of the gully is shown in Fig. 2.

2.2. Instrument and collection of data

The hydrological data used in this research included precipitation, runoff, and sediment. These data were dated 1987 to 2010 and were provided by the Tianshui Soil and Water Conservation Station. As shown in Fig. 1, four digital rain gauges were installed in the watersheds to record rainfall. In order to record the flow rate of runoff, a trapezoidal flume was constructed at the outlet of QW, while a triangular flume was built to enhance measuring accuracy at the outlet of QE (see Fig. 3). Using water level and flow velocity measurements, the flow rate was computed using Eq. (1):

$$Q = \alpha VA. \quad (1)$$

where α is the flow velocity adjusting factor; and A is the cross-sectional area calculated from the measured water level and channel shape parameters. The α equals 0.85 and 0.65, as determined by the

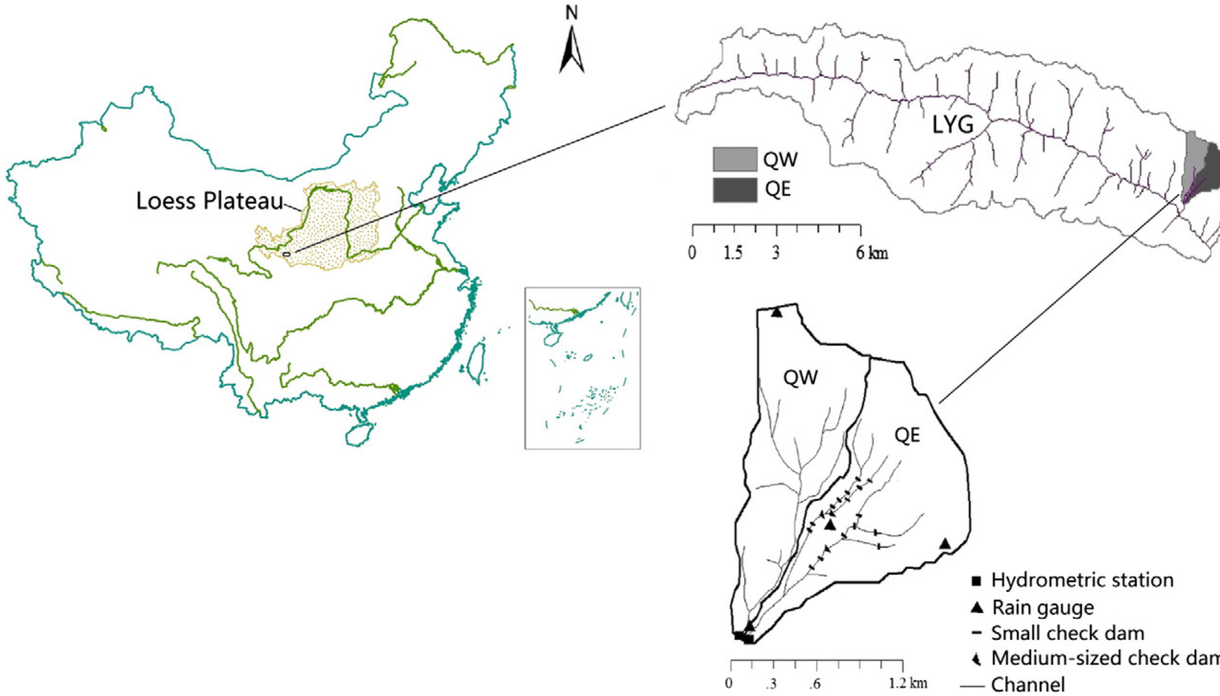

Fig. 1. Location of the study site.

Yellow River Institution of Hydraulic Research, YRCC, Zhengzhou, for low and high flow rates, respectively.

Suspended sediment concentration (SSC) was then derived from runoff flow samples using the gravimetric method, wherein the sediment-laden water samples were oven-dried at 105 °C for 24 h. Finally, the delivery of suspended sediment was calculated according to SSC and flow rate.

2.3. Watershed management practices and land use change

The QE has been influenced by WMP since 1987. This watershed contains terraces, forestation, and grassland. The vegetation and slope soil control practices have been implemented in QE since 1985, and then three medium-sized check dams built in 1992 were filled up in 1993. In 2005, 19 more check dams were constructed and started functioning in QE, including 2 medium-sized and 17 small check dams (Fig. 1). The medium-sized check dams range from 500 to 600 m^3, and the small-sized check dams range from 100 to 300 m^3. The overall capacity is around 5000 m^3, which could silt up around 13,000 t of sediments. The QW has no soil conservation practices. The local farmers have planted about 0.023 km^2 of cherry trees on terraces, which to some extent reduces soil erosion.

Table 2 depicts the data regarding the difference in land use/coverage between QE and QW in 1985 and 2006. In 1985, QE was mainly used as sloped cropland, terraces, woodland, and grassland. Fig. 4 shows the watershed management practices in QE. By 2006, the amount of sloped cropland and terraces decreased significantly by 49.75 and 15.02%, respectively. However, the amount of woodland and grassland increased by 61.52 and 0.48%, respectively. In QW, the land was predominantly sloped cropland (77.46%) in 1985. In 2006, however, sloped cropland, terraces, and grassland decreased by 41.04, 2.14, and 0.48%, respectively. Meanwhile, woodland increased by 46.72%.

Table 2 indicates the changes in land use by QE and QW. In QE, sloped cropland, residential area, and unused land are 31.97, 2.09, and 7.97% smaller than those in QW, respectively. Woodland, terrace, grassland, and road are 38.48, 0.37, 2.90, and 0.28% higher than those in QW, respectively.

Table 1
Main geographic information regarding QE and QW, with and without WMP, respectively.

Watershed	Area (km^2)	Length (km)	Width (km)	Channel gradient (%)	Relative difference in elevation (m)	Gully density ($km\ km^{-2}$)
QE	1.36	2.00	0.68	8.0	377	5.13
QW	1.09	2.18	0.50	8.0	377	5.09

2.4. Data analysis

This study uses a data set from 1987 to 2010. During this period, the total numbers of runoff events were 152 and 183 in QE and QW, respectively. Given the lack of data on some flood events, 143 flood events were selected for both QE and QW. All statistical analyses were performed using SPSS 13.0 software (SPSS Inc., Chicago, IL, USA).

The Mann–Kendall test (Mann, 1945; Kendall and Gibbons, 1990) is one of the widely used distribution-free tests of trend in time series. Distribution-free tests have the advantages that their power and significance are not affected by the actual distribution of the data (Hamed, 2009). This is in contrast to parametric trend tests, such as the regression coefficient test (Matalas and Sankarasubramanian, 2003), which assumes that the data follow the normal distribution and whose power can be greatly reduced in the case of skewed data (Yue et al., 2002). The Mann–Kendall test has therefore been widely used for testing trends in many natural time series that deviate significantly from the normal distribution, such as temperature, rainfall, river flow, and water quality time series.

The stationarity of the data was analyzed by the nonparametric Mann-Kendall test based on the computation of Mann's rank statistic (Kendall and Stuart, 1979): x_1,……, x_n represent the data points. The numbers n_i of elements x_j precede each element x_i ($j < i$) such that $x_j < x_i$ is obtained. Under the null hypothesis (no trend), the test statistic is calculated by

$$t_k = \sum_{i=1}^{i=k} n_i \quad (2)$$

Fig. 2. The gully of study area.

This statistic is normally distributed, with mean and variance given by

$$\bar{t}_k = E(t_k) = k(k-1)/4 \tag{3}$$

$$\mathrm{var}(t_k) = \overline{\delta t}_k^2 = k(k-1)(2k+5)/72 \tag{4}$$

assuming that

$$u_k = \left(t_k - \bar{t}_k\right)/\left(\overline{\delta t}_k^2\right)^{1/2}. \tag{5}$$

Given this normalized variable, probability α_1 is then calculated:

$$\alpha_1 = \mathrm{prob}(|u|>|u_k|). \tag{6}$$

If α_0 is the significance level of the test (e.g., $\alpha_0 = 0.05$), the null hypothesis is either accepted or rejected depending on whether $\alpha_1 > \alpha_0$ or $\alpha_1 < \alpha_0$. A significant change in the values of u_k indicates either an increasing ($u_k > 0$) or a decreasing trend ($u_k < 0$) in the data. The sequential version of the test used in this study can approximate trend time by determining the intersection of the direct and backward curves of the test statistic within the confidence interval (Demaree and Nicolis, 1990).

The sequential version of this test is graphically done. The curves of the statics $u(t)$ and $u^*(t)$, which are computed using Eq. (5), are displayed. These curves correspond to direct and retrograde time series. The $u(t)$ statistic denotes the evolution of the analyzed series over time. The $u^*(t)$ is plotted to localize the beginning of the change at the intersection between the curves. The starting point is significant if it falls between the critical values of the confidence interval $-1.96 < u(t) < 1.96$ (1.96 corresponding to $\alpha_0 = 0.05$).

Furthermore, annual sediment delivery per unit runoff (C_{RS}, kg m^{-3}), which is the ratio of annual sediment delivery to annual runoff yield, represented the relationship between runoff and sediment delivery in the watershed. Thus, the annual variation between QE and QW can be analyzed with respect to this relationship.

The relationship between runoff and sediment delivery can be expressed in terms of annual and event scale (Zheng et al., 2008). The relationship between the total runoff volume and the total sediment load for a calendar year is considered as the runoff–sediment relationship at the annual scale. Accordingly, the relationship between the total runoff volume and the total sediment load for a given rainfall event is regarded as the runoff–sediment load relationship at the event scale. Likewise, the relationship between flow rate and sediment concentration is interpreted as the runoff–sediment concentration relationship at event scale.

3. Results

3.1. Annual scale

3.1.1. Annual relationship between rainfall and runoff

Fig. 5 depicts the annual precipitation and runoff depth in QE and QW from 1987 to 2010. Over the study period, average annual precipitation was 542.5 mm. Fourteen and four annual runoff depths were less than 1 mm in QE and QW, respectively. In 1988, the maximum runoff depths of QE and QW were 21.5 and 37.0 mm, respectively. Generally, the runoff followed the same qualitative, but not quantitative, trend for the two watersheds: an exception appears in 1992–1993. The reason is that three medium-sized check dams were built in QE in 1992, which impounded runoff significantly, resulting in the runoff coefficients (0.12% in 1992 and 0.15% in 1993) were lower than that in QW (2.60%

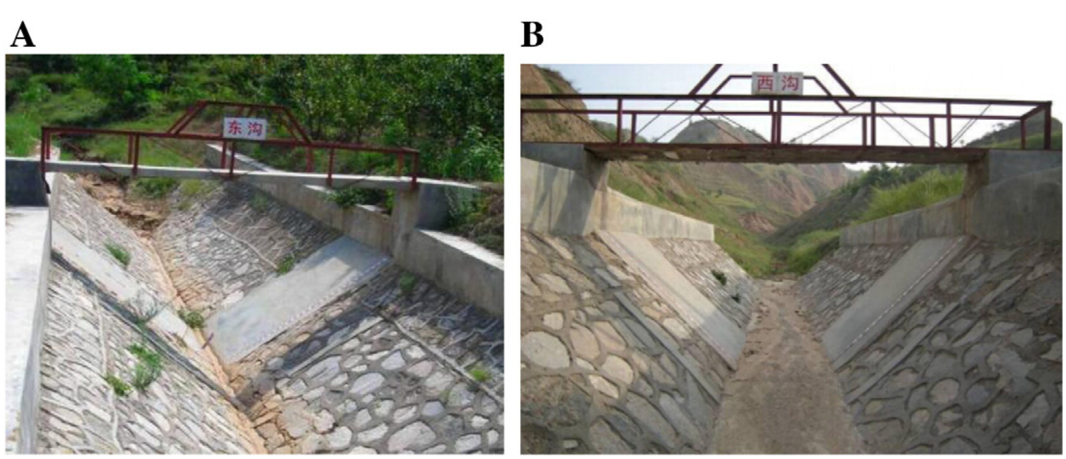

Fig. 3. Watershed management practice (WMP) in QE: (A) check dam and (B) vegetation.

Table 2
Different land use in the study watersheds[a].

Year	Watershed	Farmland		Woodland	Grassland	Residential area	Road	Unused land
		Sloped cropland	Terrace					
1985	QE	54.20%	16.08%	26.23%	2.42%	0.23%	0.00%	0.84%
	QW	77.46%	2.83%	2.55%	0.48%	2.14%	0.00%	14.54%
2006	QE	4.45%	1.06%	87.75%	2.90%	0.29%	1.84%	1.71%
	QW	36.42%	0.69%	49.27%	0.00%	2.39%	1.56%	9.68%
Variance ratio	QE	−49.75%	−15.02%	61.52%	0.48%	0.06%	1.84%	0.87%
(2006 vs. 1985)	QW	−41.04%	−2.14%	46.72%	−0.48%	0.25%	1.56%	−4.86%

[a] Land use data were provided by the Tianshui Soil and Water Conservation station.

in 1992 and 1.68% in 1993; see Fig. 6). However, the three check dams filled up with sediment in 1993, and then the runoff in QE followed the same qualitative trend as that in QW.

Fig. 6 displays the relationship between annual precipitation and runoff depth in QE and QW during the study period. In terms of runoff depth and precipitation, the variances of QE and QW are 47 and 56% respectively, and the linear regressions were significant ($P < 0.001$). The regression coefficient of QE was less than half that of QW. The relationship of linear regression between the annual runoff coefficients of QE and QW also indicates that the value of the runoff coefficient of QE was less than half of that of QW (Fig. 7).

The Mann–Kendall test considers annual precipitation and the runoff coefficients of QE and QW (Fig. 8), with their values of $u(t)$ significantly lower the confidence limit (<−1.96) in the periods of 1996 to 1999, 1992 to 2001, and 1995 to 2001, respectively. Over the study period, the mean values of $u(t)$ of the time series of precipitation and of the runoff coefficients of QE and QW were −0.75, −1.57, and −1.32, respectively. Thus, the time series of the runoff

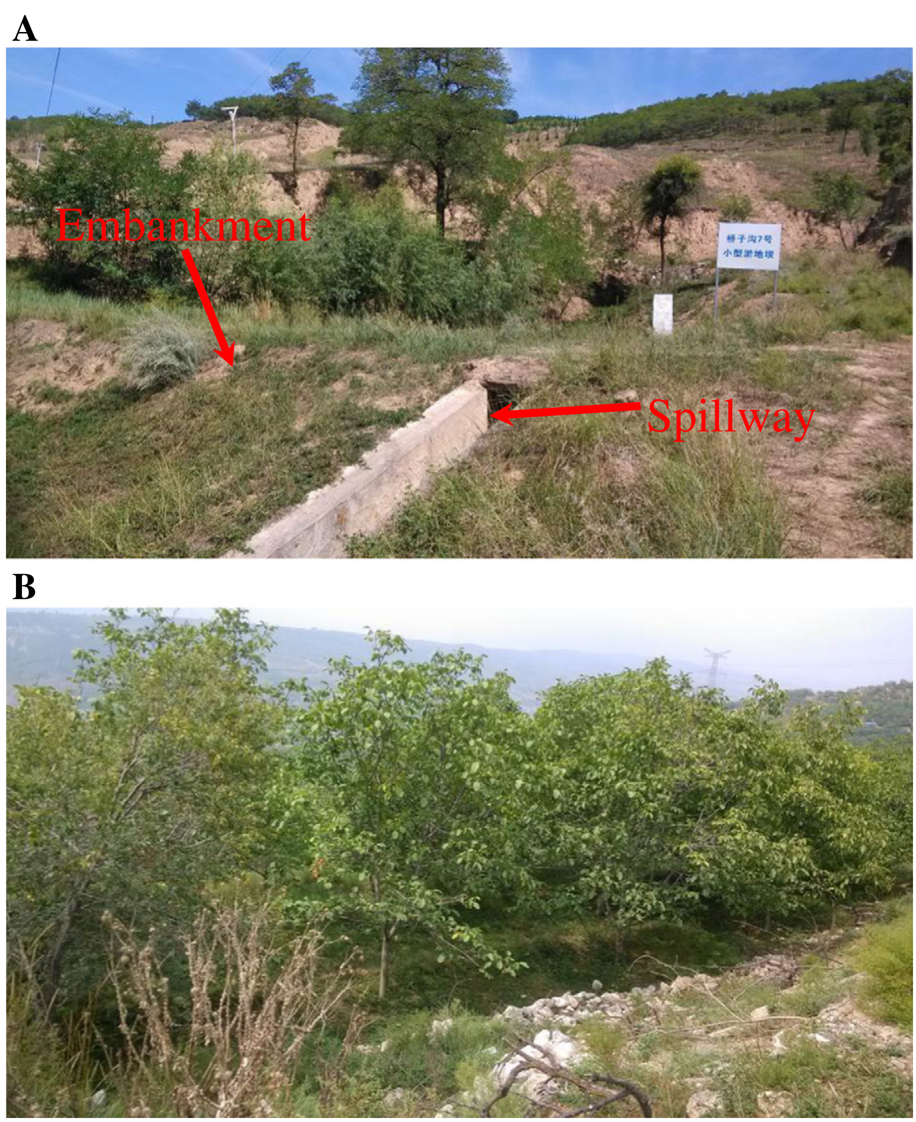

Fig. 4. The outlet of (A) QE and (B) QW.

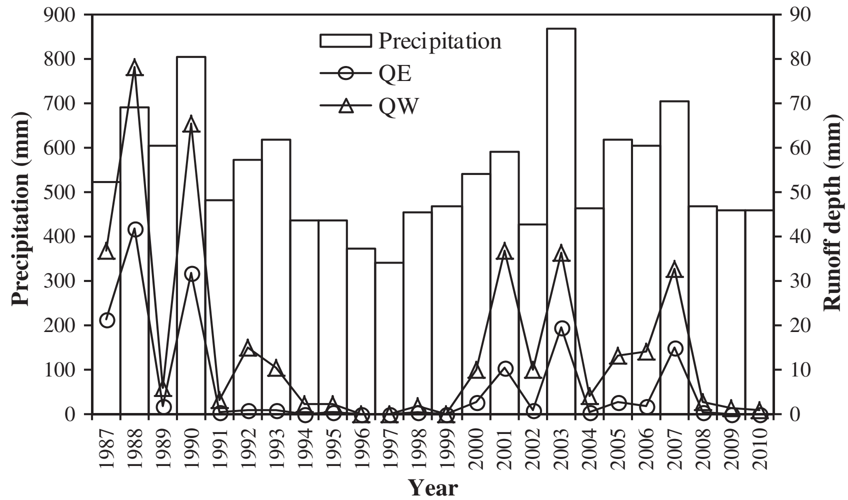

Fig. 5. Annual precipitation and runoff depth of QE and QW, with and without watershed management practices respectively.

coefficient in QE decreased significantly, followed by the runoff coefficient in QW and precipitation.

3.1.2. Relationship between annual runoff and sediment delivery

In QE and QW, the determination coefficients were higher than 0.9, thus indicating that the relationship between runoff depth and specific sediment yield is significant (Fig. 9). In terms of this relationship, QE and QW did not differ significantly given almost equal linear coefficients in general. However, two aberrant values occur in QE at low runoff while the two values occurred in 2009 and 2010, respectively. The main reason is that the annual precipitations were small (458.5 mm in 2009 and 458.3 mm in 2010), and the annual runoff and specific sediment yield were reduced dramatically in QE because of watershed management practices, especially with check dams.

Figs. 10 and 11 depict a double-mass plot and the results of the Mann–Kendall test, respectively. The slope gradient declined after 2004 (Fig. 10) thereby suggesting that annual sediment delivery per unit runoff decreased from 2004 onward. In 2007, this reduction was significant. The results of the Mann–Kendall test agreed with this finding. The two curves of Mann–Kendall statistics were calculated for the forward and backward statistical sequences and are plotted against time in Fig. 11. Curve $u(t)$ represents statistics for the C_{RS} time series, and $u^*(t)$ denotes that for the backward C_{RS} time series. If the curves intersect within the confidence interval, a jump change point is observed (Moraes et al., 1998). Fig. 11A shows that the two QE curves intersected in 2004, thus indicating that the C_{RS} of QE abruptly decreased from this year onward. In 2004, low annual precipitation (462.5 mm) caused low annual runoff depth and specific sediment yield. The net runoff was 0.5 mm, producing 62.2 t/km^2 sediments, with 6 flood events. The decreasing trend observed from 2007 to 2010 is highly significant when the absolute values of $u(t)$ are larger than the confidence limits (ABS $(u(t)) \geq 1.96$). The annual precipitations in 1989 (607.6 mm), 1993 (619.3 mm), 2005 (606.7 mm), and 2006 (619.3 mm) were about the same. But the ratios between specific sediment yield and runoff depth in 1989 (377.6 kg/m^3) and 1993 (344.8 kg/m^3) were about three times of those in 2005 (126.7 kg/m^3) and 2006 (118.9 kg/m^3), indicating that the relationship between runoff and sediment delivery was altered by the check dams. This result confirms that the relationship between runoff and sediment delivery in QE was greatly altered by WMP from 2007 to 2010. Furthermore, from 2008 to 2010, the sediment delivery per unit runoff in QE declined to below 100 kg m^{-3}.

In QW, the values of $u(t)$ were all within the confidence limits ($-1.96 < u(t) < 1.96$) at the significance level $\alpha_0 = 0.05$, thereby suggesting that the relationship between runoff and sediment delivery did

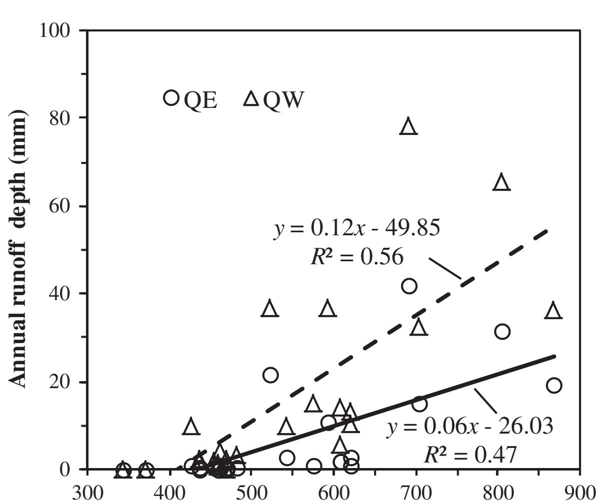

Fig. 6. Annual relationships between precipitation and runoff depth in QE and QW.

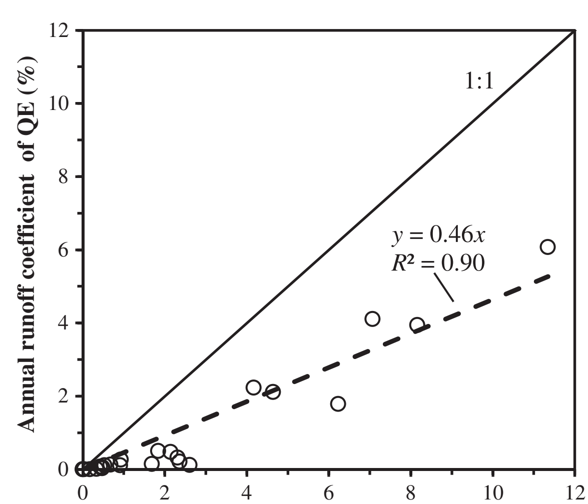

Fig. 7. Annual relationships between the runoff coefficients of QE and QW.

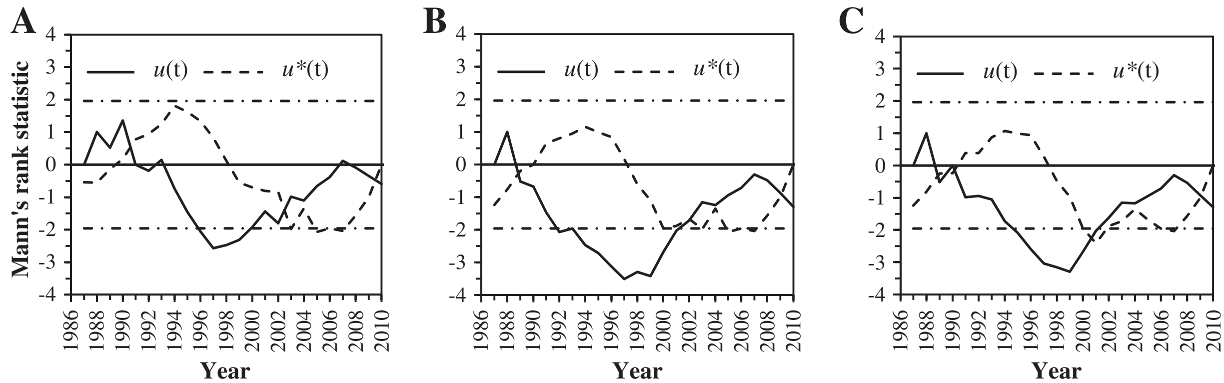

Fig. 8. Sequential trend test of Mann–Kendall conducted on the forward (full line) and backward (broken line) time series of (A) precipitation and (B) runoff coefficients of QE and (C) QW over the study period. The horizontal dash-dotted lines represent the critical values corresponding to the 5% significance level.

not change significantly from 1987 to 2010. Fig. 11B shows that the two QW curves intersected in 2005, thus indicating that the C_{RS} of QW abruptly decreased from this year onward. The decreasing trend observed from 2005 to 2010 is not significant when the absolute values of $u(t)$ are smaller than the confidence limits (ABS $(u(t)) < 1.96$). This result indicates that the relationship between runoff and sediment delivery in QW was not greatly altered by vegetation practice and slope terrace practice from 2005 to 2010.

3.2. Event scale

3.2.1. Relationship between rainfall and runoff based on event

The value of the runoff coefficient of QE was less than half of that of QW (Fig. 12), as observed in the linear regression relationship between these coefficients at the event scale. However, the runoff coefficient of QE was higher than that of QW in three flood events, and the runoff coefficients of QE were almost equal to that of QW in the other three flood events. This finding is ascribed to the positive correlation of runoff coefficient with antecedent soil moisture (Macrae et al., 2010), which increased as a result of high rainfall events prior to these flood events.

The Mann–Kendall test was conducted on the runoff coefficients of QE and QW at event scale (Fig. 13). During the floods from 2007 to 2010, the values of $u(t)$ in QE all decreased significantly to below the confidence limit. However, the values of $u(t)$ in QW all remained within the confidence limits, thus suggesting that the runoff coefficients of QW did not decline significantly at event scale.

3.2.2. Relationship between runoff and sediment delivery based on event

Fig. 14 exhibits the relationships between runoff depth and specific sediment yield in QE and QW at event scale. The relationship between annual runoff and sediment delivery changed significantly from 2007 to 2010. Therefore, the study period (1987 to 2010) was divided into two subperiods (1987 to 2006 and 2007 to 2010) for further study based on event scale. During the period of 1987 to 2006, a significant linear relationship was observed between runoff depth and specific sediment yield in QE and in QW. The determination coefficients were high at $R^2 > 0.9$. The regression coefficient values of QE and QW were similar, indicating that QE and QW did not differ significantly with respect to the relationship between runoff and sediment delivery at event scale. From 2007 to 2010, the data points in QE deviated considerably from the regression line of 1987 to 2006, especially in relation to flood events with low runoff depth (<0.1 mm). This result indicates that the relationship between runoff and sediment delivery was highly reduced in low runoff but that the effect was weaker in high runoff. In the same period, the data points in QW were distributed closely to the regression line, with the exception of one flood event with low runoff depth. Thus, during the period of 2007 to 2010, the relationship between runoff and sediment delivery in QW remained consistent with that during the period of 1987 to 2006.

The mean SSCs of QE and QW were tested at event scale (Fig. 15). In QE, the values of $u(t)$ were all lower than the confidence limit during flood events from 2007 to 2010, thereby suggesting that mean SSC decreased significantly. However, the values of $u(t)$ in QW all remained within the confidence limits, indicating that mean SSC did not decrease significantly.

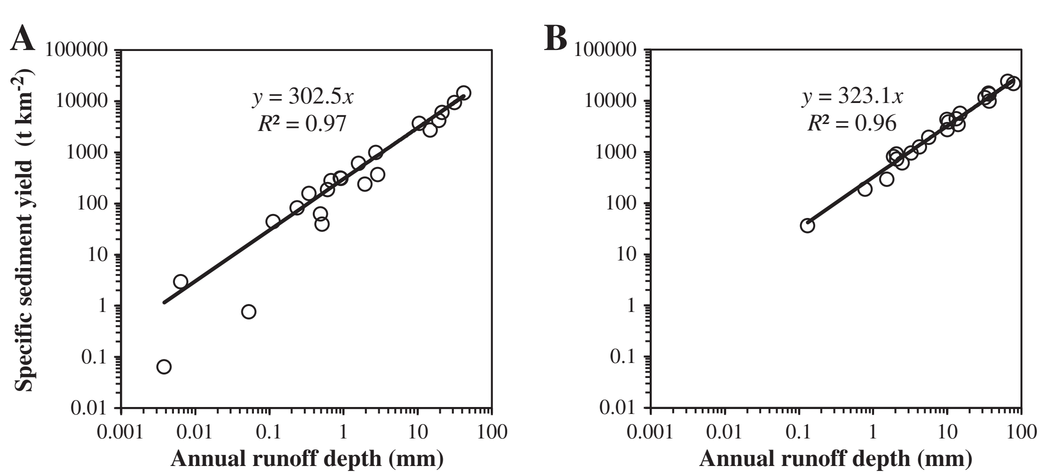

Fig. 9. Relationship between annual runoff depth and sediment delivery in (A) QE and (B) QW.

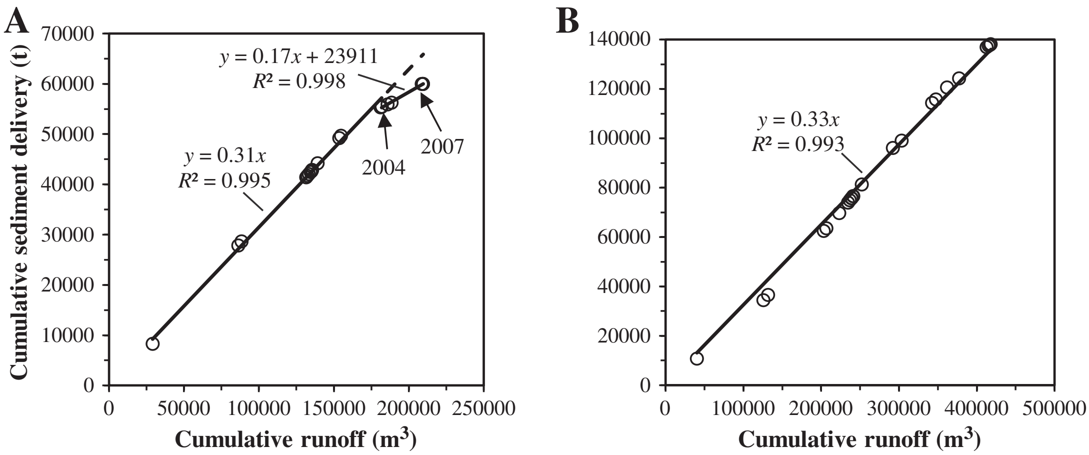

Fig. 10. Double-mass curves of runoff and sediment in (A) QE and (B) QW.

The relationship between runoff and sediment delivery can be explained further by the relationship between flow rate and SSC. Fig. 16 shows the relationships between the flow rate and SSC of QE and QW. In QE, SSC varied greatly with lowered flow rate from 1987 to 2006, whereas it remained stable when flow rate increased. The flow rate was lower (<0.1 $m^3 s^{-1}$) during the period of 2007 to 2010 than during the period of 1987 to 2006. Therefore, SSC declined as well (Fig. 16A). In QW, the distribution of data points during the period of 2007 to 2010 was similar to that during the period of 1987 to 2006.

4. Discussion

4.1. Effects of WMP on the relationship between rainfall and runoff

Factors that affect runoff include vegetation interception, the roughness of soil surface, depression storages, soil infiltration, and evaporation (Kirkby, 2002; Dunjó et al., 2004; Descheemaeker et al., 2006). Vegetation practices enhanced vegetative coverage in watersheds (Xin et al., 2008; Table 2), which changed the surface roughness, the root system, and wormholes and improved soil properties (Wen et al., 2005; Li and Shao, 2006; Liu et al., 2012), further increasing infiltration and reducing the runoff (Bochet et al., 1998; Gyssels and Poesen, 2003; Gyssels et al., 2005; Mohammad and Adam, 2010). Thus, this practice effectively altered the relationship between rainfall and runoff. Figs. 7 and 12 show that the runoff coefficient of QE was significantly lower than that of QW at annual and event scales, respectively, although the natural conditions of both watersheds are similar. These results might be because of the interception phenomenon, which decreases the velocity of raindrops and prevents them from directly impacting the soil surface in a way that splashes the soil particles. In addition, some raindrops that are intercepted by plants might evaporate directly to the atmosphere and never reach the soil (Sriwongsitanon and Taesombat, 2011). Further, high vegetative cover slows the overland flow, and the root systems of trees and shrubs play an important role in decreasing runoff by improving soil characteristics such as soil porosity and organic matter content, thus increasing the infiltration rate and decreasing the runoff (Mohammad and Adam, 2010).

Check dams can impound runoff to effectively reduce the flood peak (Dunjó et al., 2004; Descheemaeker et al., 2006). In QE, these dams influenced the relationship between rainfall and runoff during low runoff; therefore, QE flow rates are typically controlled to below 0.1 $m^3 s^{-1}$ (Fig. 16A). In high runoff, however, the capacity of check dams to hold runoff is limited. This capacity is gradually reduced because of siltation. Approximately 10% of runoff was impounded by the check dams, and these results agree with those of previous studies on the hilly-gully region of the Loess Plateau. The maximum annual runoff was generated by high-intensity rainfall events (Cai et al., 1998; Zheng et al., 2008). From 2007 to 2010, only two runoff events produced runoff depths of above 1 mm in QE. All runoff from the upper reach of QE was impounded in the check dams, including the runoff from 8 August 2007, which was the highest with a precipitation level of 88.7 mm and a runoff depth of 7.31 mm. The catchments of these 19 check dams measured 1.1 km^2 and constituted 80.9% of the QE area. These dams reduced runoff considerably from 2007 to 2010, particularly at the start (Xu et al., 2004). During this period, the runoff coefficient of QE was lower than that of QW.

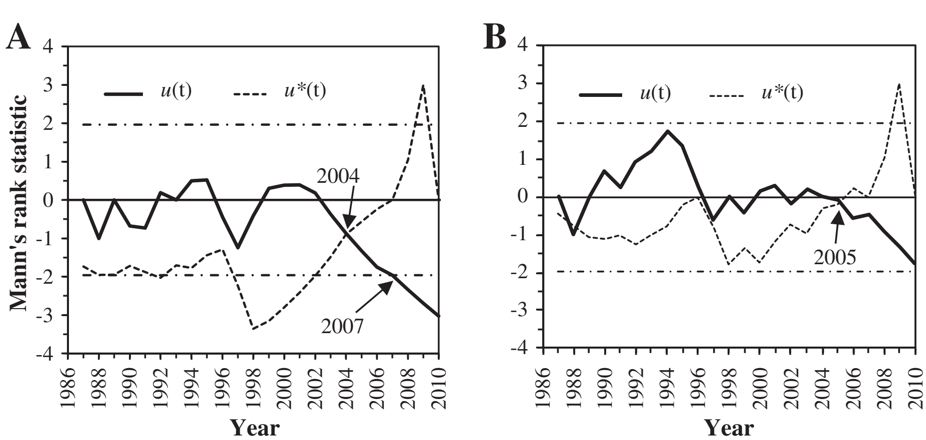

Fig. 11. Sequential trend test of Mann–Kendall conducted on the time series of annual sediment delivery per unit runoff in (A) QE and (B) QW over the study period.

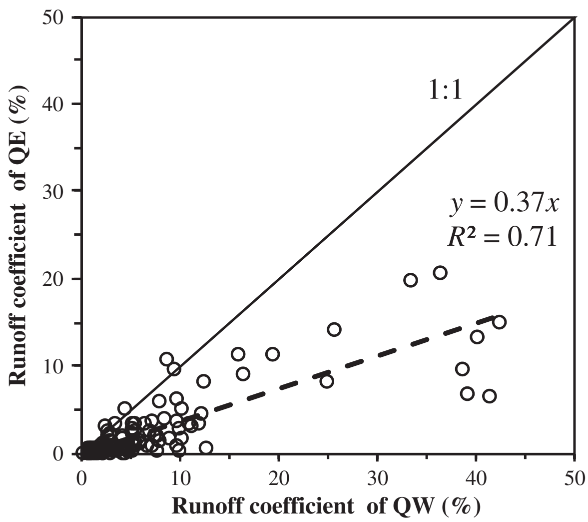

Fig. 12. Relationship between the runoff coefficients of QE and QW at event scale.

4.2. Effects of WMP on the relationship between runoff and sediment delivery

Vegetation practices effectively control erosion (Dunjó et al., 2004; Hao et al., 2004; Zheng et al., 2007b; Zhu et al., 2007; Jin et al., 2008). Vegetation controls soil erosion by means of its canopy, roots, and litter components; erosion also influences vegetation in terms of the composition, structure, and growth pattern of the plant community (Gyssels et al., 2005; Mohammad and Adam, 2010). Vegetative canopy covers and surface litter intercept raindrops to reduce their impacts on the soil surface, significantly enhancing infiltration and reducing ground roughness (Bochet et al., 1998; Gyssels and Poesen, 2003). To withstand the scouring of flowing water, plant roots can also greatly enhance soil stability. Nonetheless, vegetation practices cannot control gully erosion; therefore, sediment concentration remains high even after these practices were established (Xu, 1998). Vegetation cannot alter the system of sediment transport in the watershed gully (Xu, 1999); especially for watersheds with high gully densities in the hilly-gully region on the Loess Plateau, gully erosion is dominant and gullies are the main channel of sediment delivery. Changing the hydraulic condition of gully and control local mass movement with vegetation practice is difficult, implying that sediment availability remains high even after vegetation is established. Changing the capacity of the sediment transport system at the watershed scale with slope conservation practices is also difficult (Zheng et al., 2007b). Consequently, vegetation and slope conservation practices cannot influence the relationship between runoff and sediment delivery in watersheds. This relationship was consistent in both QE and QW during 1987 to 2006; and the relationship remained constant in QW throughout the entire study period (Figs. 10 and 14). Thus, the relationship between runoff and sediment delivery did not change with the increase in vegetation cover and terraces in either QE or QW. This result agrees with that of Zheng et al. (2007b), which postulates that vegetation and other slope practices did not affect the relationships between runoff and sediment delivery in watersheds.

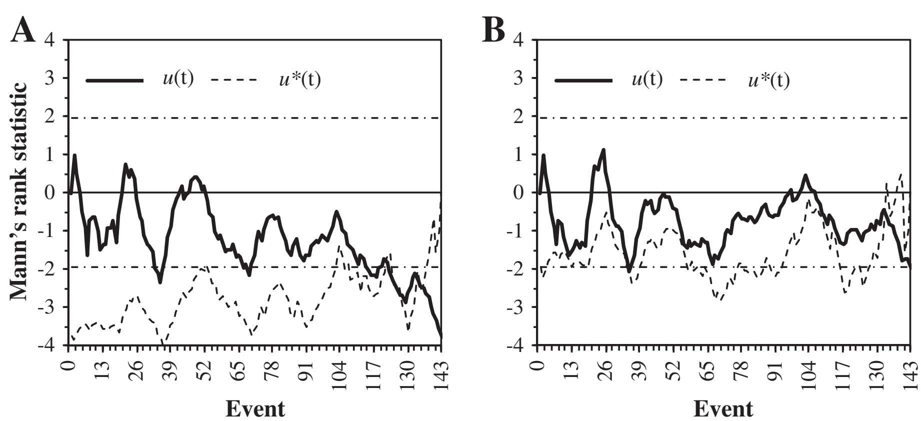

Fig. 13. Sequential trend test of Mann–Kendall conducted on the time series of the runoff coefficients of (A) QE and (B) QW over the study period based on event scale.

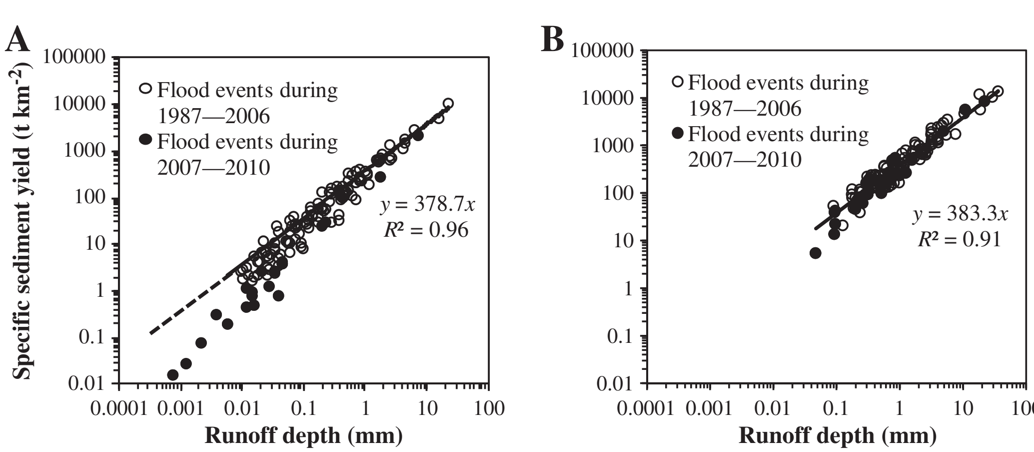

Fig. 14. Relationship between runoff depth and sediment delivery in (A) QE and (B) QW at event scale.

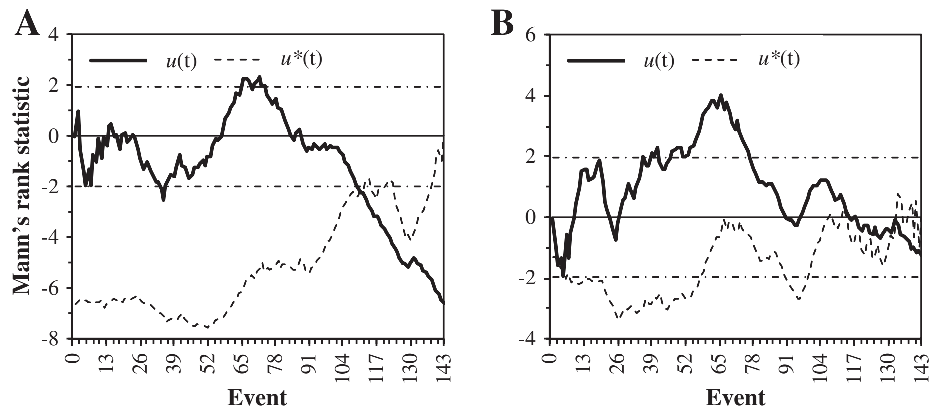

Fig. 15. Sequential trend test of Mann–Kendall conducted on the time series of the mean SSC of flood events in (A) QE and (B) QW over the study period.

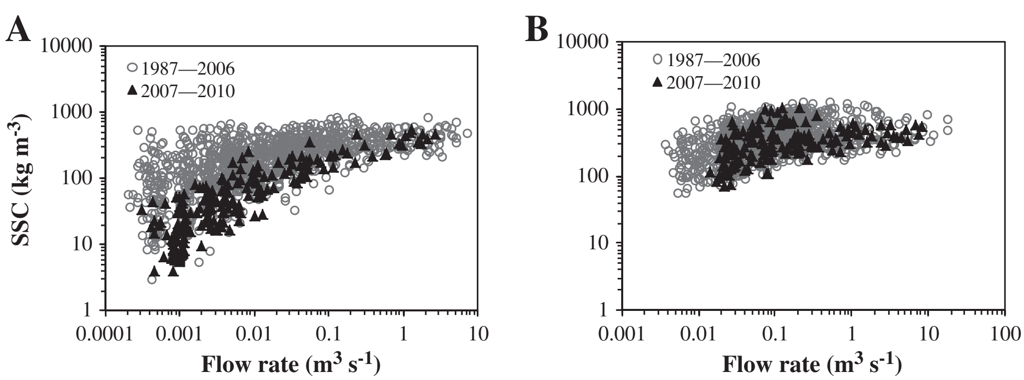

Fig. 16. Relationship between flow rate and suspended sediment concentration (SSC) in (A) QE and (B) QW.

However, vegetation practices indirectly reduced sediment delivery by limiting runoff.

Check dams can control gully erosion effectively (Xu et al., 2004; Boix-Fayos et al., 2007). These dams changed channel morphology (Boix-Fayos et al., 2007; Castillo et al., 2007) and affected the hydrological performance of the watershed, as well as soil erosion (Hessel et al., 2003; Stolte et al., 2003). When runoff is impounded, its erosion capability is reduced. As a result, sediments were collected behind the dams. This process reduces sediment delivery in watersheds by reducing the flood peak and hyperconcentrated flow (Xu, 2002). Therefore, sediment concentration in QE was lowered during the period of 2007 to 2010 because the flow rates of runoff events were mostly controlled to below the critical value (Fig. 16A). In QE, the flood peak exceeded 0.1 $m^3\ s^{-1}$ in only three runoff events, which occurred on 8 August 2007 and 29 August 2007. Hence, check dams significantly affect the relationship between runoff and sediment delivery in QE during low runoff, but the effect weakens in high runoff (Fig. 14A). This result could be attributed to the limited capacity of check dams to retain runoff and sediment during extreme rainfall. The location of the check dam is also important in controlling sediment transport. Check dams situated at the middle or upper reaches of watersheds cannot control the sediments produced at the lower reach of the channel. Although the check dams reduced the length of the channel for sediment transport, channel morphology in the lower reach does not change. As a result, channel length remains adequate for sediment harvesting from hillslope, production and transport from runoff to the watershed outlet.

5. Conclusion

Watershed management practices can effectively reduce runoff and sedimentation in the watersheds of the hilly-gully region of the Loess Plateau. The relationship between rainfall and runoff in watersheds is strongly affected by vegetation, and the runoff coefficients of watersheds decrease with the increase in vegetation cover. Vegetation practices did not alter the relationship between runoff and sediment delivery, but reduced sediment concentration in low runoff. Check dams influenced the relationships between rainfall and runoff and between runoff and sediment delivery in low runoff by reducing runoff and lowering sediment concentration. Thus, the combination of vegetation practices and check dams can control gully erosion and sediment transport effectively in areas with high erodibility, such as the hilly-gully region of the Loess Plateau.

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