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Effect of rainfall variation and landscape change on runoff and sediment yield from a loess hilly catchment in China

Wei Wei · Liding Chen · Handan Zhang · Jin Chen

Abstract The semiarid Chinese Loess Plateau is notorious for severe drought, water erosion, and environmental degradation. Changes in landscape patterns and rainfall are key drivers that determine the dynamics of runoff loss and sediment yield from catchments. These factors have crucial implications for management of other fragile ecosystems around the globe. In this study, responses of surface runoff and sediment yield to land use and rainfall in a typical loess hilly catchment in 1997, 2005, and 2010 were analyzed. Several major findings are highlighted. First, most rainfall occurred in the growing season from June to September and increased only slightly during the observation years. Second, runoff and soil transport rates at the catchment outlet from June to August were far greater than in other months. A similar trend was observed for seasonal rainfall occurrence, indicating that the intra-annual water erosion patterns were largely dominated by monthly rainfall distribution. Third, compared with the time period 1997–2005, mean runoff and sediment transport modulus in 2005–2010 declined significantly. This can be attributed mainly to changes in land use/land cover, i.e., increases in forests, shrubs, and grasses, and decreases in sloping farmlands. Dam construction is also key in controlling runoff and sediment yield, but more attention must be paid to its possible negative environmental effects. In general, our study indicates that marked changes in landscape patterns and vegetation coverage may contribute to long-term soil loss dynamics, and intra-annual rainfall variation mainly contributes to monthly variation in runoff and sediment yield.

Keywords Land use change · Rainfall · Sediment yield · Surface runoff · Loess Plateau

Introduction

Surface runoff and sediment yield have been recognized as major on-site soil degradation processes in many dryland ecosystems around the world, especially in the context of accelerated global change (Lal 1998; Yair and Kossovsky 2002; Foley et al. 2005; Kerr 2007). Such hydrological behaviors can induce severe land degradation, causing widespread decline in soil quality and environmental deterioration (Aksoy and Kavvas 2005; Cotler and Ortega-Larrocea 2006). Through particle disaggregation and soil leaching, the transport of large amounts of soil organic material to the lower river reaches can deteriorate agricultural productivity, pose problems for food security, and lead to eutrophication of aquatic environments, increase turbidity, and even contribute to carbon release and climate change (Bewket and Sterk 2003; Boix-Fayos et al. 2009). For example, according to a study conducted in Ethiopia, 1,493 million tonnes of soil is lost annually due to water erosion, and 4 mm of fertile surface soil is lost each year (Hurni 2000). In mainland China, soil erosion affects an area of 3.6×10^6 km^2 (approximately 37 % of the land), causing serious ecological problems, particularly in the

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semiarid Loess Plateau and other zones with fragile climate systems (Chen et al. 2007; Ouyang et al. 2010).

Many studies have shown that water and sediment transport are influenced by multiple factors. Land use and rainfall, however, are the two factors most frequently mentioned (Nearing et al. 2005; Foley et al. 2005; Wang et al. 2008). For example, the implementation of land use conversion projects such as reforestation and farmland terracing has reduced runoff and sediment yield by 20–100 % and 10–100 %, respectively (Zhang et al. 2010). Comprehensive land use adjustments, including forestation, sloping land conversion, and dam construction, have greatly reduced the effect of upper soil loss on the lower reaches of the Yellow River (Xu et al. 2004; Li and Wei 2011; Zhou and Zhao 2012). Over the past several decades, the effects of land use change on runoff and sediment yield across different spatiotemporal scales have been widely investigated and modeled (Chaplot et al. 2005; Beguería 2006; Rijsdijk et al. 2007). In general, research on water erosion dynamics shows that both rainstorms and anthropogenic disturbances may contribute a great deal to the total amount of soil loss, but the underlying mechanisms remain unclear (Descroix and Gautier 2002). Runoff and sediment yield would be expected to increase with increased precipitation and decreased forest coverage (Wei et al. 2009; Zhang et al. 2010). Rainstorms with kinetic raindrop potentials interacting with stark slopes will certainly boost soil particle removal, increasing water yield and sedimentation to downstream areas (Wang et al. 2010; Nunes et al. 2013). In some cases, natural weather events such as severe rainstorms are considered to be the most important factor, whereas in other cases, human forces play a strong role. For example, the leading cause of water erosion and landslides in natural ecosystems is considered to be prolonged and torrential rains (Philpott et al. 2008). Human civilization was established in the Loess Plateau of China for thousands of years and has greatly reshaped the local landscape and influenced the local environment. Accelerated soil erosion is mostly attributed to human activities such as overgrazing, deforestation, and sloping cultivation, which are often associated with vegetation withdrawal and land cover reduction (Shi et al. 2009).

In the face of local environmental problems, public concern has risen during recent years (Chen et al. 2013). However, traditional monitoring and analysis of runoff and soil erosion take place mainly at small scales, such as field/plot measurements (Nearing et al. 2005). Such data can only represent the magnitude of soil and water loss at particular sites that interact with their surroundings. Aside from plots and slopes, soil loss also occurs at ditches, gullies, and channels within catchments, and these sources also make major contributions to sediment yield at watershed outlets (Yair and Raz-Yassif 2004; Chen et al. 2007).

Field-scale erosion measurements and related analysis cannot replace soil loss studies at the level of catchments and other spatial scales. In order to control erosion and limit environmental degradation, it is important to determine the mechanism of soil–water loss at least at the catchment scale.

Determining soil and water loss from a whole catchment is beneficial for erosion research and integrated watershed management because of the integrality and unit independence of topographical boundaries. Small catchments provide the further advantage of convenient field investigation and data collection (Yair and Kossovsky 2002; Shi et al. 2012). Measuring changes in water erosion to changes in land use and rainfall at the catchment scale is helpful for solving problems in agriculture, forestry, water resource allocation, and other key land usage issues (Fox and Papanicolaou 2008).

The Loess Plateau of China, which is located in the upper and middle reaches of the Yellow River, has long been considered very fragile area that suffers from severe drought and water erosion (Fu 1989; Zhou et al. 2006; Chen et al. 2007; Zhou and Zhao 2012). Because of its extensive erosion, it is an excellent subject for case studies of soil and water loss. In order to control soil erosion and improve the local environment, the Chinese government launched a series of projects such as "grain to green" and "natural forestland protection" at the end of the 1990s. These efforts have greatly changed the landscape pattern during the past decades. However, the potential environmental effects of such changes in land use/cover remain unclear and merit further study.

In this study, a typical loess hilly catchment was selected for detailed investigation and analysis. There were three main goals: (1) to determine how monthly rainfall variation affects runoff and soil transport rates, (2) to determine how landscape change (land use/cover, dam construction) affects soil and water loss within the catchment, and (3) to discuss the dual role of rainfall variation and landscape change in affecting water erosion at the catchment scale.

Materials and methods

Study area

Our study was conducted at the Anjiagou Catchment (104°38′13″–104°40′25″E, 35°33′02″–35°35′29″N), located in Dingxi, Gansu province, in the western part of the Chinese Loess Plateau (Fig. 1). This area has long suffered from severe water erosion, and has a typical loess hilly environment. Great changes in land use/cover have also taken place under the influence of intense human activity

Fig. 1 Geographical location of study area
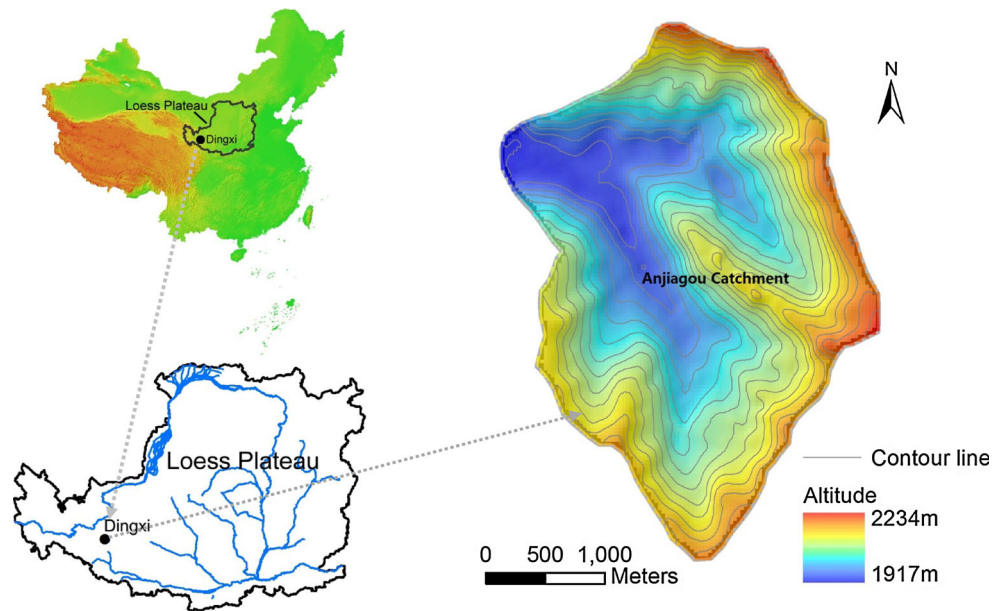
during the past decades. Long-term hydrological data are available within the catchment. The total area of the catchment is 8.97 km^2. It is dominated by a semiarid, temperate terrestrial climate with warm, humid summers and cold, dry winters. The average annual precipitation is approximately 427 mm (according to the 50 year mean value), of which more than 80 % occurs in the rainy season (May to September), with an annual variability of 25.8 %. Annual transpiration, however, can reach 1,510 mm, making this region extremely dry. Mean air humidity is approximately 65.8 %, and there are typically 141 frost-free days. The annual sunshine duration is 2,409 h, and the mean monthly temperature varies from −7.6 to 27.5 °C, with a mean annual value of 6.3 °C.

Soil type in the catchment depends on the wind-accumulated loess parent material, the depth of which varies from 40 to 60 m (Chen et al. 2007). According to the American soil classification system, this type of soil is defined as a calcic Cambisol because it has a clay content of 33.1–42.2 %, 4–13 g/kg of organic matter and a soil bulk density ranging from 1.09 to 1.36 g/cm^3 within a depth of 2 m. The soil structure is loose and porous, and the landform in the catchment is complex and fragmented, making this area vulnerable to severe soil erosion.

Due to poor climate conditions (e.g., drought and erosion) and a history of human land use activities (e.g., deforestation, overgrazing, and sloping cultivation), plant succession and vegetation growth in the catchment have been very limited. The effect of human activity is more significant than natural factors, which should be stressed here. For the past several centuries, human agricultural activities have accelerated soil erosion significantly. Fortunately, this behavior was altered when the local population gradually realized the importance of maintaining a healthy and sustainable environment, particularly in the 1990s. Since then, integrated watershed management programs have been broadly implemented and strengthened, with the goals of controlling erosion and reducing poverty. Sloping farmlands in the catchment and in other neighboring regions were gradually abandoned, and the land used instead for planting trees, shrubs, and grasses or converted into terraced farmland.

Local field studies indicate that there are 79 wild and 64 cultivated plant species in the catchment, belonging to 23 plant families. The major planted tree species in the study area are Chinese pine (*Pinus tabuliformis* Cart.), Chinese arborvitae (*Platycladus orientalis* L.), and wild apricot (*Prunus armeniaca* L.). The shrub species are mainly sea buckthorn (*Hippophae rhamnoides* L.) and pea shrub (*Caragana kansuensis* Pojark.). The major herbaceous plant species are alfalfa (*Medicago sativa* L.), sainfoin (*Onobrychis vichfolia* Scop.), and bunge needle grass (*Stipa bungeana* Trin.). The major cultivated crops in the region are spring wheat (*Triticum aestivum* L. Cv Leguan), potatoes (*Solanum tuberosum* L.), maize (*Zea mays* L.), and flax (*Linum usitattssimum* L.).

Data monitoring and collection

A hydro-meteorological field station was established in Anjiagou Catchment in the mid-1980s for long-term field monitoring and data collection. The field station belongs to the Dingxi Institute of Soil and Water Conservation. Basic

meteorological, soil physiochemical, hydrological, and erosion data are monitored and recorded at this station by automatic instruments.

The specific details of each rain event over a 14-year period (1997–2010) were recorded using rainfall instruments, including an MDZH4T tilting bucket raingauge, an SM_1 pluviometer, and an SJ_1 auto-siphon udometer. Rain events separated by more than 6 h were considered to be separate events. Due to the small size of the catchment study area, the spatial variation of the rainfall was ignored. The recorded variables (depth, duration, intensity, and MI_{30}) were compared, and mean values were used for further analysis.

The outlet runoff and sediment were also collected. A trapeziform trough was built at the outlet to collect real-time data. Each runoff and soil loss event was monitored by the trough during the rainy season. Events of different sizes were treated differently. For small rainfall events, the runoff was collected and measured in barrels. For severe rainstorms, runoff was calculated based on a marked buoy and flooding velocity measurement. For both situations, turbid water samples were collected with a 250-ml measuring flask, and the samples were used to estimate water and sediment transportation.

Detection of landscape change in image

One set of aerial photographs (taken in September 1997), one set of TM images (taken in September 2005), and one ALOS satellite images (taken on September 1, 2010) were used for landscape analysis. In order to interpret the three image types at the same scale, a re-sampling method was first used to obtain the same spatial resolution (30 m × 30 m). Meanwhile, field sample investigations were conducted to correct and validate the image interpretation. In total, 110 field points were orientated to capture the land use information using a GPS instrument. These samples were distributed evenly within the catchment and covered all the land use types. Then, the images were interpreted on the basis of a local 1:10,000 landform map and supervised classification. After calibration, the interpretation accuracy can reach 84.3 %.

Finally, 3 years of land use/cover change (LUCC) data were captured and analyzed using the platforms ERDAS and ARCGIS. Based on spatial overlay analysis, several related digital maps were created, and the LUCC dynamics were analyzed. Land use type was classified based on the national criteria of the resource and environmental database of the Chinese Academy of Sciences. According to the rules and the specific features of Anjiagou Catchment, land use was divided into 8 major types: terraced lands (TL), sloping farmlands (SL), forestlands (FL), scrublands (SL), grasslands (GL), residential areas (RA), bare land (BL), and water bodies (WB). In addition, a digital camera was used to collect vegetation cover data at the same field sites during the growing season each year. Due to the relatively small coverage area, annual land cover in the catchment was estimated as the mean value of the 110 sample points.

Statistical methodology

Statistical analyses were performed in Excel 2007 and SPSS 16.0. The characteristics of natural rainfall events were analyzed using a descriptive statistics module. The ANOVA and Correlation and Regression Analysis modules were used to quantify the contribution of rainfall and landscape change to the outlet runoff and sediment transport rates, respectively.

In addition, two mathematical equations were used to calculate the mean annual surface runoff modulus (SRM: units of $m^3\ km^{-2}$ for event value and $m^3\ km^{-2}\ year^{-1}$ for annual mean value) and sediment transport modulus (STM; units of $t\ km^{-2}$ for event value and $t\ km^{-2}\ year^{-1}$ for annual mean value) at the catchment outlet.

$$SRM = \sum_{j=1}^{n} \left(SR_j \middle/ CA \right) \tag{1}$$

$$STM = \sum_{j=1}^{n} \left(SY_j \middle/ CA \right) \tag{2}$$

In these equations, n, SR_j, SY_j, and CA refer to the total annual runoff generation number, surface runoff volume in the jth event, sediment yield at the catchment outlet in the jth event, and the area of total covered catchment (km^2), respectively.

Results

Specific rainfall features

Based on the long-term meteorological and hydrological data, total rainfall for each month in Anjiagou Catchment during the 14-year study period was calculated (Fig. 2). It was found that the rainfall varied greatly and was distributed unevenly across different months and seasons. For most years, most of the rainfall was concentrated in the growing season (May to September), and the greatest rainfall occurred in June, July, and August. These rainfall data indicate that the climate conditions in the local area follow a smooth time series and show no clear inter-annual changes (increases or decreases; Fig. 2).

Non-erosive and erosive rainfall events were distinguished by measuring data directly in the field. Those

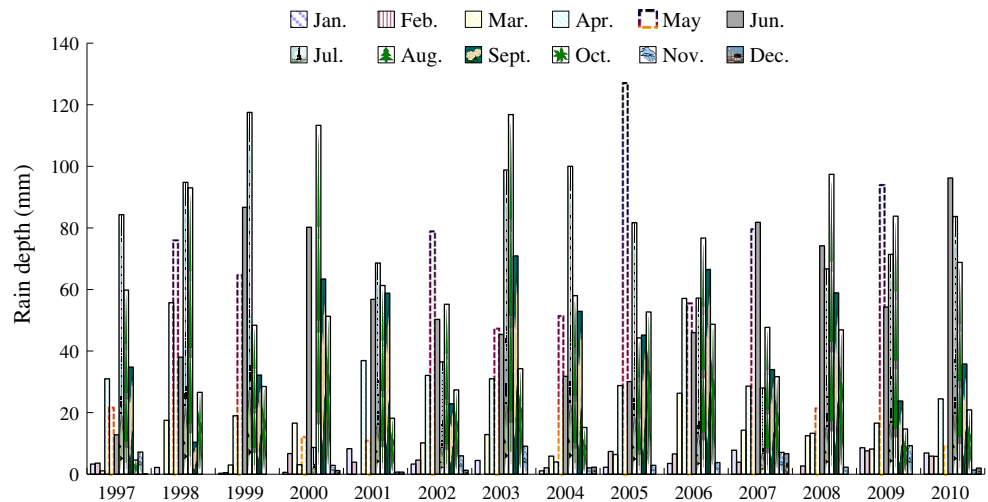**Fig. 2** Monthly rainfall amounts in different years in the study area

Table 1 Descriptive statistics of daily erosive rainfall features

Period	Index	Range	Minimum	Maximum	Sum	Mean	SE[a]	SD[b]	CV[c]
1997–2005	Depth (mm)	41.8	5.1	46.9	1031	19.5	1.55	11.27	0.58
	Duration (min)	2,020	20	2,040	29,376	554	71.16	518.08	0.93
	Intensity (mm/min)	0.94	0.01	0.95	5.38	0.10	0.02	0.08	0.79
	MI_{30} (mm/min)	0.92	0.03	0.95	11.88	0.22	0.03	0.18	0.78
2005–2010	Depth (mm)	72.3	7.6	79.9	1,119.6	21.5	1.83	13.16	0.61
	Duration (min)	4,295	35	4,330	35,061	674	96.24	593.98	0.88
	Intensity (mm/min)	0.34	0.01	0.35	2.98	0.06	0.01	0.04	0.71
	MI_{30} (mm/min)	1.03	0.02	1.05	10.62	0.20	0.03	0.17	0.85

[a] Standard error

[b] Standard deviation

[c] Coefficient of variance

rainfall events with the power to generate runoff and water loss were defined as erosive ones based on the actual data measured in situ (Wei et al. 2009). In order to analyze the specific features of erosive rain events in the catchment, the descriptive statistics of such events in the two mentioned periods were analyzed (Table 1).

As shown in Table 1, the key variables include rainfall amount, intensity, maximum rain intensity within 30 min (MI_{30}), and duration of erosive rainfall events, all of which varied greatly during the two typical periods. The mean quantity and duration of erosive rainfall events in the later time period (2005–2010) were determined to be 21.5 mm and 674 min, respectively, much greater than that observed in the earlier time period (1997–2005). The mean intensity and MI_{30}, however, were found to have opposite roles compared to depth and duration. Mean rain intensity and MI_{30} during the later time period (2005–2010) were 0.06 and 0.20 mm/min, respectively. In the earlier time period (1997–2005), mean rain-intensity and MI_{30} were 0.10 and 0.22 mm/min, respectively. Furthermore, ANOVA (LSD)

analysis indicated no significant difference ($P > 0.05$) between key rainfall variables for the two periods, confirming that there was no clear trend of change in natural rainfall during the 14-year study period (Table 2).

Landscape change in the catchment

In this study, three sets of aerial and satellite images taken in 1997, 2005, and 2010 were collected and interpreted for further analysis. Land use patterns in the three selected years were captured (Fig. 3; Table 2). In 1997, TL, SF, FL, SL, GL, RA, and BL covered 48.66, 10.95, 4.19, 7.10, 4.28, 4.93, and 19.89 %, respectively. No water body (WB) appeared in 1997. The spatial data from 2005 and 2010 showed that TL, SL, and BL were greatly reduced with time, while four other land use patterns (FL, SL, GL, and WB) increased during these years. In contrast to 1997, an area of WB appeared in 2005 and increased slightly in 2010, mainly because a dam was built in 2004 within the catchment. RA in the catchment, in contrast, increased

Table 2 ANOVA (LSD) analysis of rainfall features

Index	Group① 1997–2005 Group② 2005–2010	Sum of squares	df	Mean square	F	Sig.
Depth	Between groups	113.333	1	113.333	0.756	0.387
	Within groups	15,445.603	103	149.957		
	Total	15,558.936	104			
Duration	Between groups	377,876.577	1	377,876.577	1.010	0.317
	Within groups	3.852E7	103	373,970.952		
	Total	3.890E7	104			
Intensity	Between groups	0.051	1	0.051	3.788	0.054
	Within groups	1.394	103	0.014		
	Total	1.446	104			
MI_{30}	Between groups	0.010	1	0.010	0.287	0.593
	Within groups	3.744	103	0.036		
	Total	3.754	104			
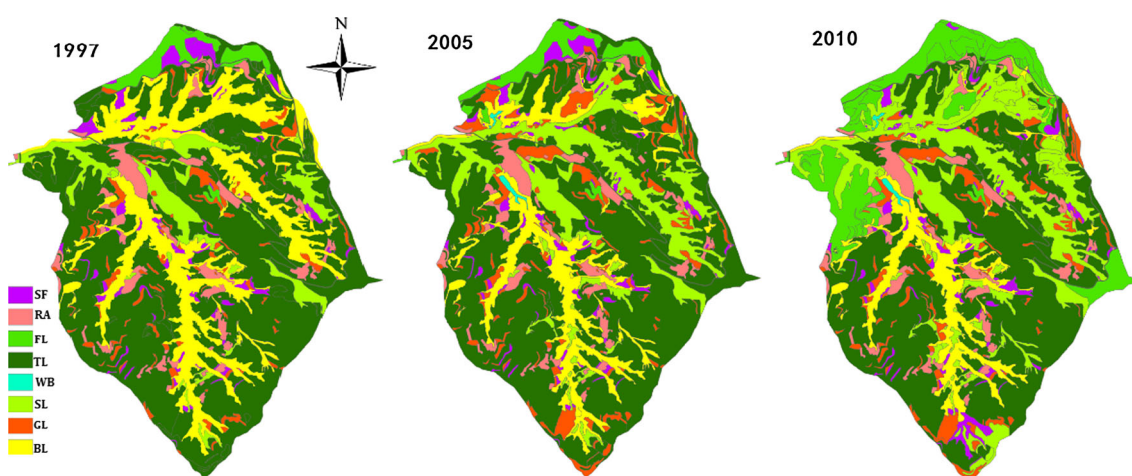
Fig. 3 Land use map of Anjiagou Catchment in the three observation periods

slightly from 1997 to 2005 and then decreased slightly from 2005 to 2010. According to a local investigation, RA remained stable and even decreased in the later time period because of the implementation of an export strategy for labor services. Young people migrated to big cities to earn money, and human disturbance was thus reduced, establishing a win–win cycle for the local economy and environment.

Changes in the percentage of each land use type were also calculated (Table 3). From 1997 to 2005, SL changed the most, followed by GL, BL, FL, TL, SF, and RA. From 2005 to 2010, FL increased the most, followed by SL, GL, and WA. In the same period, SF, BL, TL, and RA decreased by 22.17, 16.93, 14.26, and 0.25 %, respectively.

Runoff and sediment yield in different periods

Total annual runoff and sediment yield were calculated for the study periods (Table 4). Compared with the earlier time period (1997–2005), several key indicators including cumulative runoff volume (CRV), total sediment yield (TSY), annual mean runoff yield (AMR), annual mean sediment yield (ASY), SRM, and STM showed that sediment transport and water loss at the catchment outlet decreased sharply in the later time period (2005–2010).

Monthly SRM values at the watershed outlet were also captured during the periods 1997–2005 and 2005–2010 (Fig. 4). The major findings were as follows: first, the mean monthly runoff modulus was very small and potentially negligible during the first 4 months of the year, with values of 0.67, 0.89, 1.34, and 5.02 m^3 km^{-2}, respectively, in the earlier time period (1997–2005). Then, it increased significantly with the arrival of the growing/rainy season (155 m^3 km^{-2} in May and 322 m^3 km^{-2} in June) and gradually reached its highest values in July (656 m^3 km^{-2}) and August (786 m^3 km^{-2}). The mean monthly runoff modulus then decreased sharply from September (101 m^3 km^{-2}) and October (4.97 m^3 km^{-2}) to November

Table 3 Characteristics of land use change in Anjiagou catchment during the study period

Land use type	Yearly covered area (10^{-2} km^2)			Relative change (%)	
	1997	2005	2010	1997–2005	2005–2010
Terraced land	442.34	404.9	347.17	−8.46	−14.26
Sloping farmland	99.58	95.23	74.12	−4.37	−22.17
Forestland	38.09	43.82	99.12	15.04	126.20
Scrubland	64.51	142.1	178.26	120.28	25.45
Grassland	38.86	63.94	70.24	64.54	9.85
Residential area	44.79	44.83	44.72	0.09	−0.25
Water body area	0	1.98	2.16	–	9.09

Table 4 Total runoff and sediment yield during the two study periods

Time period	Key soil–water loss index at the catchment scale					
	CRV[a]	TSY[b]	AMR[c]	ASY[d]	SRM[e]	STM[f]
1997–2005	164,241	65,547	18,249	7,283	2,034	812
2005–2010	13,752	11,802	2,292	1,967	256	219

[a] Cumulative runoff volume (m^3)

[b] Total sediment yield (kg)

[c] Annual mean runoff yield (m^3)

[d] Annual mean sediment yield (kg)

[e] Surface runoff modulus (m^3 km^{-2} year^{-1})

[f] Sediment transport modulus (t km^{-2} year^{-1})

Fig. 5 Mean monthly sediment transport modulus during the study period

The mean seasonal STM during the two periods (1997–2005 and 2005–2010) were also captured (Fig. 5). Like the SRM, the monthly watershed-scale STM varied by season and period. Generally, the STM values were very small for the first 3–4 months (January to April), with mean values varying from 2.2 to 22 t km^{-2} year^{-1} in 1997–2005 and 1.7 to 14 t km^{-2} year^{-1} in 2005–2010. The STM increased markedly during the major rainy season of the year, from May to August. In 1997–2005, the mean STM increased gradually from May to August, whereas the related STM values in the same 4 months decreased by 234, 457, 512, and 552 t km^{-2} year^{-1} in the later time period, respectively. From September to December, however, the STM values in each of the two periods decreased rapidly, and some of them were so small as to be negligible.

Discussion

Contribution of rainfall features to outlet soil transport

The contributions of rainfall variables to surface runoff and sediment yield have long been studied across different scales around the world (Nearing et al. 2005; Beguería 2006; Wei et al. 2009). Natural rainfall parameters and their regimes were confirmed as the initial and essential drivers of risks, tracks, and degrees of soil erosion and surface hydrology. In this study, simply comparing the results shown in Fig. 2 with those in Figs. 4 and 5 indicates that the distribution and degree of rainfall and the monthly SRM and STM were consistent and isochronous. Inter-annual rainfall features determine the specific variations of runoff volume and sediment yield across different months and seasons. Meanwhile, specific rainfall variables, such as rainfall amount, duration, and intensity, may play different roles in runoff generation and soil erosion across different scales of space and time (Yair and Raz-Yassif 2004; Bracken et al. 2008). On the basis of Pearson correlation
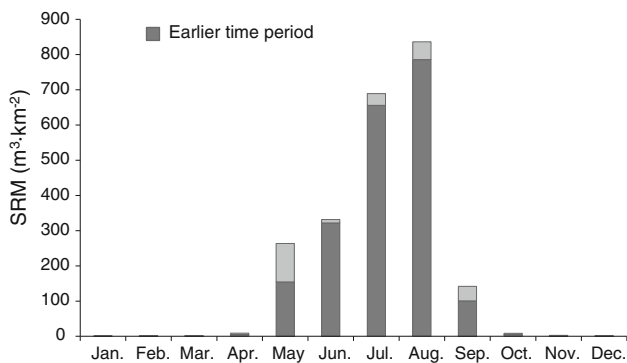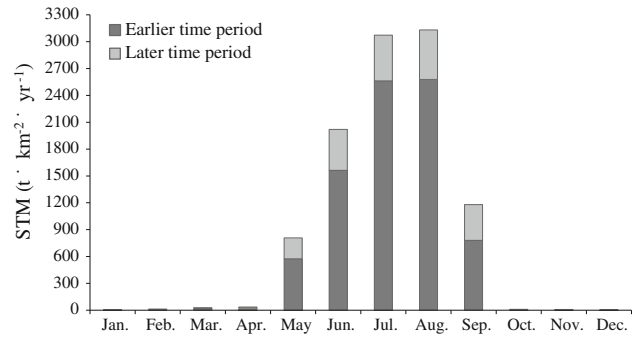

Fig. 4 Mean seasonal outlet runoff coefficient during the study period

(1.60 m^3 km^{-2}) and December (1.28 m^3 km^{-2}). Second, the monthly runoff moduli were sharply reduced in the later time period compared with the earlier time period. For example, the highest value of the mean runoff modulus in the later time period was 109 m^3 km^{-2}. This value occurred in May and was far lower than what was observed in the earlier time period.

analysis, it was found that the contributions of key natural rainfall variables to STM differed from one another at the catchment scale (Table 5). For example, the correlation coefficient between rainfall duration and STM was −0.047, with a 0.731 non-significant P value. However, the correlation between rainfall amount and STM and the correlation between MI_{30} and STM were both significant. Statistical tests showed that the latter (MI_{30}) may contribute more to STM than rainfall amount (Fig. 6). Many studies also confirmed that various rainfall variables make different contributions to water erosion in other similar regions. For example, at the watershed scale, rainfall intensity was found to have positive correlations with sediment yield and runoff loss rate. Sediment concentration is stronger when heavier rainfall appears, mainly due to higher detachability capacity (Aksoy and Kavvas 2005).

Effects of land use/cover change on outlet soil and water loss

Our results indicate that land use change has significant effects on runoff and sediment yield (Table 3; Figs. 3, 4, 5). This can be partly attributed to increases in FL, SL, and GL and decreases in SF and BL within the catchment. The mechanisms explaining how landscape change affects water and sediment transport are as follows. Changes in land use can greatly shift landscape patterns and actual vegetation cover, thus altering the partitioning of rainwater through vegetation and soil into the critical hydrological components of interception, infiltration, total evaporation, surface runoff, and groundwater recharge (Symeonakis et al. 2007; Wang et al. 2008; Yu et al. 2010; Shi et al. 2012). The surface hydrology and soil erosion responses of an integrated catchment, on the other hand, are dependent on the whole landscape pattern, which is also sensitive to changes in land cover (Shi et al. 2009). For example, Zhang et al. (2010) found that sediment yields in four loess hilly watersheds all decreased following the implementation of reforestation and sloping-farmland terracing projects, even when the precipitation amount increased from 350 to 650 mm in the same period. Proper land use can greatly reduce water erosion potential and risk, while land mismanagement can greatly increase these risks.

Runoff and sediment loss declined significantly when land cover increased (Fig. 7), indicating a strong inverse relationship between sediment yield and land cover (Yan et al. 2013). Studies in other climatic zones and geographic regions also support this conclusion. For example, Yu et al. (2010) reported that a 10 % increase in forest coverage can lead to a 13 % reduction in runoff volume, and runoff reduction was estimated to reach a maximum of 60 % if the forest coverage increased from 0.41 to 46.1 % at the watershed level in an arid region. After analyzing several studies conducted in different humid areas of the world, it was concluded that forestation can cause an average of 44 % (±3 %) reduction in annual runoff (Farley et al. 2005). Using a paired watershed approach, cumulative runoff yield in the treated watershed was reduced by approximately 32 % as a result of afforestation (Huang et al. 2003). In India, soil erosion potential was slightly increased from 1211 to 1,321 t km^{-2} $year^{-1}$, mainly due to the disappearance of a forest patch and an increase in steep sloping wasteland (Sharma et al. 2011).

Effect of check-dam construction on runoff and sediment reduction

Check-dam construction, a powerful tool for altering natural hydrological processes, plays a key role in sediment retention and water conservation in catchments (Lien 2003; Castillo et al. 2007). It was once believed to be the most effective way to conserve soil and water in the Chinese Loess Plateau (Chen et al. 2007). In this study, a dam system (4.41 km^2 controlled area, with dimensions of 20.5 m height, 4 m width and 89.7 m length) was built within Anjiagou Catchment at the end of 2004 (Fig. 8). After the dam was completed, soil and water loss from the catchment continued to decline significantly (Figs. 4, 5). Moreover, a water body in the catchment was observed by satellite imaging and found to cover an area of

Table 5 Pearson correlation between rainfall and outlet soil loss

Index	Pearson correlation	Duration	Depth	MI_{30}	STM
Duration (min)	Correlation coefficient	1	0.520[a]	−0.372[a]	−0.047
	Sig. (2-tailed)	–	0.000	0.002	0.731
Depth (mm)	Correlation coefficient	0.520[a]	1	0.181	0.237[b]
	Sig. (2-tailed)	0.000	–	0.063	0.014
MI_{30} (mm/min)	Correlation coefficient	−0.372[a]	0.181	1	0.443[a]
	Sig. (2-tailed)	0.002	0.063	–	0.000
STM (t km^{-2} a^{-1})	Correlation coefficient	−0.047	0.237[b]	0.443[a]	1
	Sig. (2-tailed)	0.731	0.014	0.000	–
Sample numbers	–	106	106	106	106

[a] Correlation is significant at the 0.01 level (2-tailed)

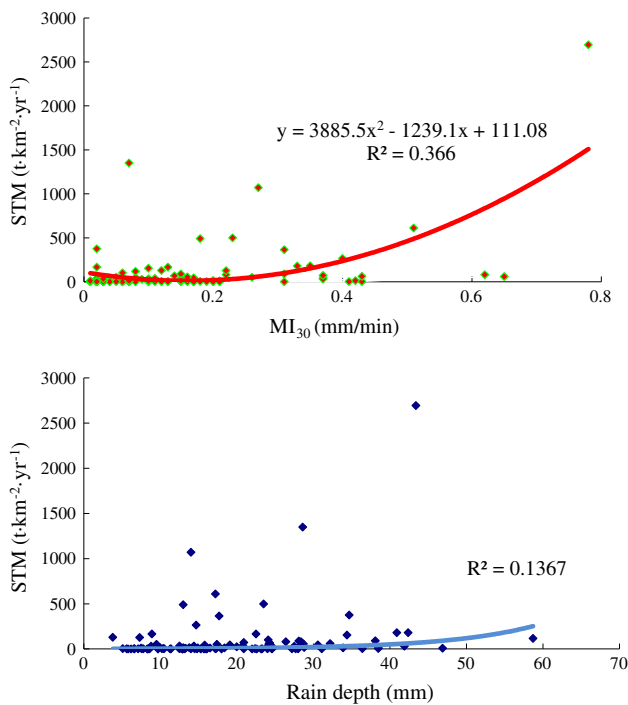[b] Correlation is significant at the 0.05 level (2-tailed)

Fig. 6 Regression relationship between rain depth, MI_{30} and STM

1.97×10^{-2} and 2.16×10^{-2} km^2 in 2005 and 2010, respectively. Due to the severe drought conditions, however, the water body and base flow never appeared before the dam was built, indicating that a man-made dam system can conserve rainwater effectively and prevent runoff out of the catchment. Because no clear changing trend in rainfall change was detected (Fig. 2; Table 2), dam construction should be considered another major contributor to the reductions in water erosion and sediment yield, along with increases in forests, shrubs, and grasslands.

Several studies have also confirmed that dams and transverse structures can hold back huge amounts of soil and water within many highly degraded catchments (Li and Wei 2011; Romero-Díaz et al. 2012). Moreover, by retaining huge amounts of soil nutrients, it was found that check-dams can improve soil fertility, reduce food crises, and improve carbon sequestration, vegetation restoration, and climatic adaptation (Boix-Fayos et al. 2009; Abedini et al. 2012; Lü et al. 2012). As a consequence, check dams were widely used to stabilize gullies and prevent downstream sediment deposition in many places around the world. By 2002, more than 7×10^8 m^3 of sediments in the Chinese Loess Plateau had been intercepted by dams (Xu et al. 2004). So far, over 10,000 check-dams have been commissioned in the whole loess region (Chen et al. 2007). In a semiarid Spanish Mediterranean catchment, check-dams built in ephemeral channels were shown to intercept huge amounts of sediment (Castillo et al. 2007).

Although check dams have the power to conserve huge amounts of soil and water in a catchment, their long-term and potential effects on local ecosystems remain unclear (Lenzi 2002; Liu et al. 2006). For example, some critics see check-dam construction as an example of strong human interference in an integrated natural ecosystem, which may greatly change the biogeochemical and hydrological cycles of the region, especially when such projects are implemented in large areas without any restrictions by environmental legislation (Chen et al. 2013). Some authors worry that such artificial structures may disrupt ecological functions and environmental stability (Siriwardena et al. 2006). Furthermore, the potential impact of the materials used for dam construction also requires long-term investigation and monitoring (Liu et al. 2006). The quality and security of constructed dams have also come under criticism from local residents (Xu et al. 2004). More scientific designs and engineering steps to improve quality should be implemented (Lien 2003; Chen et al. 2007). In summary, more careful work and detailed studies are needed before artificial dams can be safely used at larger scales.

Coupling role of landscape change and rainfall variation in runoff and sediment yield

In the semiarid Loess Plateau and other fragile ecosystem zones around the world, there is increasing concern for how changes in climate factors and land use combine to affect local environments and related biogeochemical processes across different scales (Nearing et al. 2005; Govers et al. 2006; Yan et al. 2013). From a systematic point of view, the coupling role of human-induced landscape change and natural variation in rainfall in water erosion becomes uncertain and complex within a catchment (Descroix and Gautier 2002; Shi et al. 2009). In most cases, however, it is difficult to quantify the specific role of each factor in determining surface runoff and sediment transport (Chaplot et al. 2005; Zhang et al. 2010).

In this study, natural rainfall was confirmed to have only a slight increasing trend during the observation years, but fluctuated around the mean value as the seasons and years passed (Fig. 2). This is the major reason for the seasonal and yearly variations of soil and water output at the catchment outlet (Figs. 4, 5). Land use/cover changes, however, dominated the long-term trends of erosion outcomes. In the catchment, owing to the implementation of "grain-to-green" and "natural forest protection" projects, as well as integrated watershed management, the land use pattern was re-adjusted, and land cover has been gradually improved since the late 1980s (Figs. 3, 7). Meanwhile, under the encouragement of a "rural labor export" policy, the majority of young people in the local area migrated to the cities to earn money, which helped to reduce human

Fig. 7 Relationship between land cover and annual runoff/sediment yield in the catchment
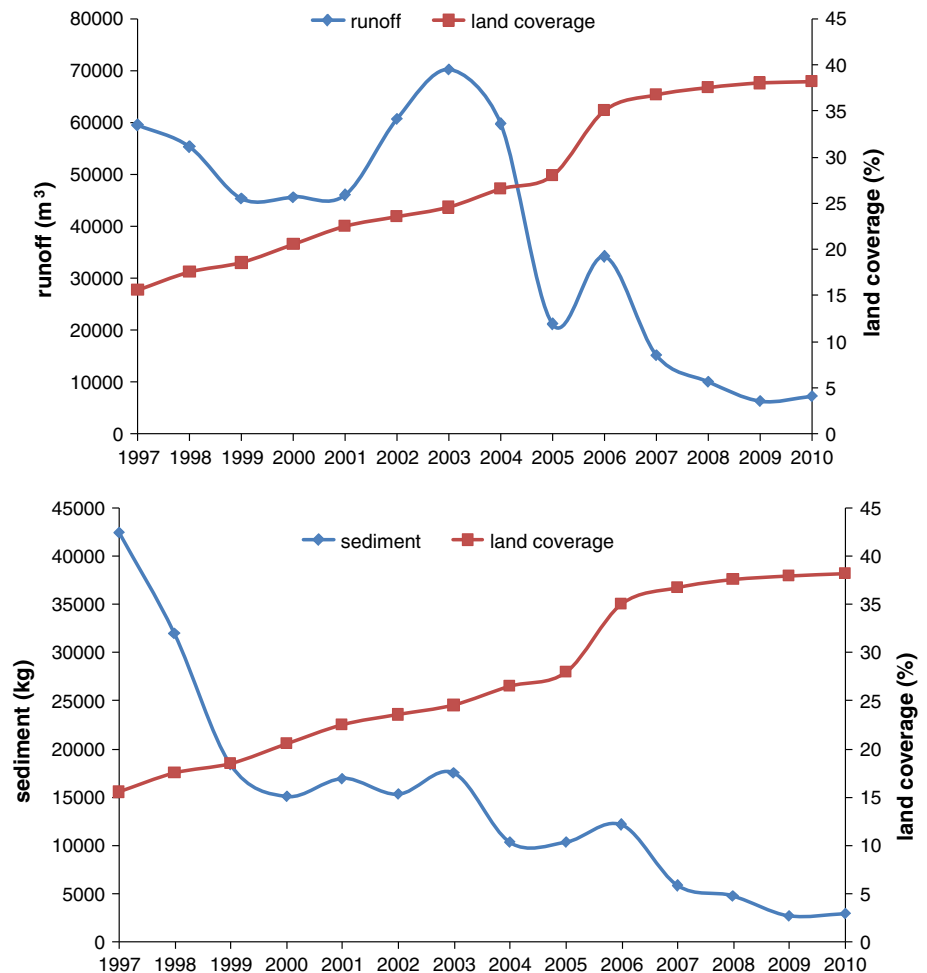

Fig. 8 A constructed dam system greatly reduced soil and water loss from the catchment (photo from 2010)

disturbances to the fragile environment. This situation also led to the enforcement of a policy of restoring sloping farmlands to green lands (forests, grasses and shrubs). All these positive measures have contributed to landscape reshaping and land cover improvement. Correspondingly, annual runoff and sediment output have been sharply reduced, even during the first several years before dams were built (Fig. 7).

Conclusions

In this study, the effects of rainfall variation and land-use change on runoff and sediment yield in Anjiagou Catchment were analyzed. The major findings are as follows: first, large changes in land use/cover have taken place in the catchment, indicating that the local environment has gradually improved. No clear trend of rainfall change was detected. Second, the highest runoff and sediment quantities were observed from June to August, far greater than during other months. This is in agreement with the seasonal rainfall, implying that seasonal rainfall patterns determine inter-annual water and soil loss in the catchment. Third, mean SRM and STM declined significantly, mainly because of the increase in surface cover caused by the enhancement of FL, SL, and GL, and the decrease in SF

and BL. Meanwhile, although dam construction plays a key role in retaining runoff and sediment, its potential negative effects on the local environment should be studied further. In general, changes in land use/cover contribute to the long-term dynamics of soil loss, whereas intra-annual rainfall dominates the variation in monthly and yearly erosion. In the context of accelerated human activity and climate change, more scientific and detailed land use planning should be implemented to control water erosion and restore natural ecosystems. The seasonal destructive role of erosive rainfall should also be considered, especially in the fragile Loess Plateau and similar semiarid environments.

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