TRANSACTIONS OF THE CHINESE SOCIETY FOR AGRICULTURAL MACHINERY
Vol. 47, No. 8, 2016

doi:10.6041/j.issn.1000-1298.2016.08.015

Effects of Different Flood Regimes on Soil Erosion and Sediment Transport in Typical Small Watershed of Loess Hilly – Gully Region

Zhang Letao[1,2] Li Zhanbin[1,3] Xiao Junbo[4] Wang Shanshan[1,2]

(1. *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Ministry of Water Resources, Yangling, Shaanxi* 712100, *China*
2. *University of Chinese Academy of Sciences, Beijing* 100049, *China*
3. *Key Laboratory of Northwest Water Resources and Environment Ecology, Ministry of Education, Xi'an University of Technology, Xi'an* 710048, *China*
4. *Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi* 712100, *China*)

Abstract: Soil erosion responses under different rainfall and runoff patterns are fundamentals for the studies of soil erosion mechanisms. To investigate the influence of flood regimes on soil erosion and sediment yield at small watershed scale, a typical small watershed—Shejiagou catchment was selected to conduct data collection and analysis, and Shejiagou is a first order tributary of Chabagou drainage basin lying in the hilly and gully region of Chinese Loess Plateau. Based on 45 individual flood events recorded at Shejiagou Hydrological Station during 1961 to 1969, all the flood events were categorized into three regimes through a combined approach of K-mean clustering and discriminant analysis with three grouping variables, including flood duration, event flood runoff depth and peak discharge. Regime A was characterized by short duration, small flood runoff depth, low flood variability and medium peak discharge, which was the most common regime. Regime B was featured with medium duration, medium flood runoff depth, medium flood variability and small peak discharge, which was of medium frequency. Regime C mainly included flood events of long duration, large runoff depth, high variability, as well as large peak discharge, which was of the lowest frequency. The regime of flood events was mainly controlled by flood duration at studied scale. Area-specific sediment yield, mean suspended sediment concentration and maximum suspended sediment concentration driven by different flood regimes can be ranked in the order of C > B > A, C > A > B, C > A > B, respectively. However, no significant difference was found among the three flood regimes for the variables examined ($P > 0.1$). The runoff-sediment relationship was relatively constant at Shejiagou watershed, the variations in suspended sediment concentration can be well described by the logarithmic function of instantaneous discharge. The sediment output at watershed outlet was mainly controlled by event-based total flood runoff. Given that event flood runoff depth was kept constant, the ratio of area-specific sediment yield driven by different flood regimes A∶B∶C was 1∶0.93∶1.22. If the flood duration was increased by 1.7 times, the flood regime-based increase for sediment yield reached the maximum, and the maximum increase rate for area-specific sediment yield was 22%. The results may provide beneficial evidence for categorization of individual flood events, and overall rational-based evaluation on the soil and water conservation benefits brought by runoff regulation systems at watershed scale.

Key words: flood regime; small watershed; soil erosion and sediment yield; runoff regulation

0 Introduction

The spatio-temporal distribution of rainfall and associated surface runoff determines the allocation pattern of flow-induced erosivity and underlying erosive energy at different temporal and spatial scales. As a result, sediment flow behavior induced by different hydrologic regimes varies across scales from sloping surfaces to drainage basins[1-6]. The theory on regulation and utilization of rainfall-runoff provides basic principles for design and implementation of anti-erosion strategies, which is of vital significance to the reestablishment of harmonious flow-sediment relationship[7-8]. Thus, rules of soil erosion in

Received date: 2015-12-09 Accepted date: 2016-03-03
Supported by National Natural Science Foundation of China (Grant No. 41330858)
Corresponding author: Li Zhanbin, Professor. E-mail: zbli@ms.iswc.ac.cn. Tel: +86-136-09259310.

regional size can be profoundly clarified and rational design and implementation of sediment control measures can also be promoted through the accurate identification of erosion responses and sediment flow behavior evolvement driven by different hydrologic regimes[2, 9-12]. Over the past few decades, major progress has been made on runoff regulation induced sediment-reducing benefits and its mechanisms on sloping surfaces, as well as runoff regulation based optimization of anti-erosion measures[13-17]. Undoubtedly, these advances have exerted positive influences on overall eco-hydrological evaluation on comprehensive management measures for soil and water conservation, associated with the improvement of integrated watershed management levels. Despite the fact that several studies have been conducted concerning sediment control benefits caused by the regulation of flood hydrographs[18], flood regime based effects on basin erosion response and sediment delivery have not yet been thoroughly revealed. Furthermore, the alteration of hydrologic regime coupled with the change of sediment flow behavior is in urgent need of deep clarification under the conditions of human-dominated eco-environment system.

Rainfall storm induced flood runoff has been recognized as the major driving force to cause basin erosion and sediment yield on the Chinese Loess Plateau, which is typical of a unique erosion environment and high erosion rate[19-20]. Generally, soil losses are mainly caused by one or several severe heavy storms on this region[21-22]. However, the intra-annual distribution of surface runoff can not be effectively controlled by integrated measures for soil and water conservation[23]. As a result, influences of intra-event based flood hydrographs on tempo-spatial behavior of sediment flow should be highlighted to facilitate an overall perception of the significance of soil erosion-alleviating systems in basin-specific water and sediment regulation. Therefore, more intensive and further studies must be extensively carried on to systematically elucidate the dynamic responses of soil erosion and sediment yielding processes under different intra-event-based flood regimes.

The loess hilly gully region possesses an arid and semi-arid landscape with dense eroding canyons, producing abundant pluvial erosion events caused by rainstorm floods. Moreover, extensively established hydrological stations with rich statistics on runoff and sediment allow the Chabagou watershed to be a desirable experimental site for conducting studies on variations of runoff-sediment relationship in the loess hilly gully region[24-25]. Thus, the Zizhou Runoff Experimental Station plays an important role in the studies on the establishment of rainstorm-induced sediment yield model at watershed scale, tempo-spatial scale effect on sediment transport, hydrologic modelling, as well as geomorphological process on this region[26-29]. Therefore, Shejiagou branch, a typical cultivated catchment without management in Chabagou watershed, was selected in this study to investigate the sediment flow behavior driven by different intra-event-based flood regimes under a near-natural condition with little human disturbance. Based on recorded hydrological observations during 1961 to 1969, intra-event-based flood regimes were divided and sediment flow behavior was examined through the method of statistical analysis. This study was aimed at further enriching the basic concept of runoff regulation, providing beneficial evidence and theoretical basis for optimized arrangement and overall evaluation on eco-hydrological benefits of comprehensive soil and water conservation measures, as well as enhancing ecological management at the watershed scale.

1 Description of the study area

The Zizhou Runoff Experimental Station which was located in Chabagou drainage basin in Zizhou County, Shannxi Province, was established in 1958 and closed in 1969. The Chabagou river, (109° 47′E, 37° 31′N), a first branch of Dalihe River, is located in the No. 1 subregion of gullied rolling loess plateau. The river basin covers a drainage area of 205 km^2 with channel length of 26.5 km, and elevations ranging from 900 m to 1 100 m. The drainage basin above Caoping Gauging Station covers an area of 187 km^2 with channel length of 24.1 km and average width of 7.22 km in symmetry, and the gully density is 1.05 km/km^2. Chabagou watershed is predominated by a semi-arid landscape with a sparse vegetation cover. The annual precipitation in the watershed averaged 480 mm with significant intra- and inter-annual variability from 1959 to 1969, and about 70% of the precipitation mainly fell during the period from June to September. The rainstorms in this area are generally typical of high intensity in short duration (up to 3.5 mm/min). The annual runoff depth from the watershed showed great intra-annual variability, and more than 62% of the runoff occurred throughout the months from July to September. The annual average temperature was 8℃, ranging from −27℃ to 38℃. There were about 183 frost days each year.

The area is generally covered by a cultivated loessial soil with particle size greater than 0.05 mm accounting for approximately 25.8%, 0.01 ~ 0.05 mm particles accounting for about 57.7%, and particle size smaller than 0.01 mm accounting for approximately 16.5%[30]. The soil is characterized by loosen texture with large porosity and easy erodibility because of the predominance of silt-sized particles. The annual sediment yield varied from 6 267 t/km^2 to 23 670 t/km^2 between 1954 and 1958 with an average yield of 15 780 t/km^2. The watershed is typical of dryland farming with low vegetation cover and devoid of soil and water conservation measures throughout 1959 to 1969. The influence of vegetation cover, crop types, and planting patterns on variations in runoff generation capacity and event-based average suspended sediment concentration was limited and varied little over the monitoring period[31-32]. Therefore, erosion effects caused by vegetation and crop factors were disregarded in the study. Shejiagou, a first-order tributary of the Chabagou river basin, covers a drainage area of 4.72 km^2 with channel length of 4.5 km, average width of 1.05 km, and average elevation of 1 037 m. The average gully channel gradient is 1.15%, and average gradient of catchment area is 44.7%. The gauging station is 0.2 km far away from the estuary. Appropriate adjustments were made for the gauging station to facilitate hydrological observations and sediment measurements. The adjusted controlling area is as follows: during 1961 to May 1964, it was 4.72 km^2; during July of 1964 to 1969, it was 4.26 km^2. The study site is shown in Fig. 1.

2 Data sources and treatments

The hydro-sediment information was derived from the observed data of rainfall, runoff and sediment in the Zizhou Experimental Office over the period of 1959—

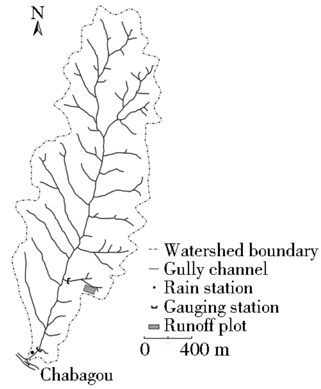

Fig. 1 Location of study area

1969. Totally 45 uniformly distributed rain gauges, and 9 nested hydrometric gauging stations were established in Chabagou basin to monitor basin precipitation process, conduct hydrological observations and sediment measurements. Rainfall events were recorded by pluviographs and detailed flow measurements were conducted using triangular weirs. The hydrological survey, sampling, and laboratory analyses in the hydrometric stations followed the international procedures for collecting all the runoff and sediment data including water stage, water discharge, suspended sediment concentration, and sediment discharge[33].

According to relevant specifications for hydrometric station[32], event-based flow hydrographs with runoff depth larger than 0.05 mm, peak discharge larger than 0.1 m^3/s, and runoff duration more than 150 min were defined as flood events. Referring to statistical tables for hydrologic processes and flood characteristics during flood seasons, 45 individual flood events were recorded in observed data of rainfall, runoff and sediment in the Zizhou Experimental Office over the period of 1961—1969. Among these events, only one event was associated with area-specific sediment yield smaller than 1 t/km^2. Therefore, all the recorded events were used in the analysis procedures. Rational variables indicative of event-based flow hydrographs and sediment dynamics were selected based on simple regression analysis on runoff-sediment relationships. All the recorded events were grouped into different classifications through a combined approach of clustering analysis and discriminant analysis on the basis of runoff-related indicators, and different flood regimes were therefore categorized. Soil erosion response and sediment dynamics were then analyzed under different flood regimes. In addition, flow-sediment relationships were established with runoff-related indicators using regression analysis method to describe flood regime driven sediment flow behavior.

Those variables that indicate flood-runoff-related characteristics, including flood duration (T, min), the time-to-peak (T_p, min), time duration of recession (T_r, min), peak discharge (q_p, m^3/s), event flood runoff depth (H, mm), mean discharge (q_m, m^3/s), and flood variability (the ratio of peak discharge to mean discharge, FV), were selected to generalize the individual flood hydrographs, whereas those variables that indicate sediment-relevant characteristics, including area-specific sediment yield (M_S, t/km^2), event-based average suspended sediment concentration (S_m, kg/m^3), event-based maximum suspended sediment concentration (S_{max}, kg/m^3), and suspended sediment concentration variability (the ratio of maximum sediment concentration to mean sediment concentration, SCV), were used as expressions of event-based sediment transport. Statistical, cluster, and discriminant analyses were conducted using the SPSS 18.0 software, by which the equations were generated. All of the graphics were plotted using the SigmaPlot 12.5 software.

3 Results

3.1 Event-based pluvial erosion and sediment yielding characteristics

Large variation scopes are generally observed for almost all the variables presented in Tab. 1 (1961—1969). Event-based flood duration ranged from 180 min to 1 680 min with an average of 638 min. Totally 6 events with flood duration exceeding 1 000 min were observed, accounting for about 13.3% of the total events. However, events with flood duration less than 600 min occurred 28 times, accounting for about 62.2% of the total events. Flood peak discharge averaged 16 m^3/s with a range of 0.13 ~ 95 m^3/s. Events with flood peak discharge less than 16 m^3/s occurred 33 times with a proportion of 73.3% in all the statistical events. However, events with flood peak discharge larger than 30 m^3/s were only observed in low frequency (6 times, 13.3%). The event flood runoff depth averaged 5.4 mm, with minima being 0.2 mm and maxima being 30.7 mm. Events with runoff depth less than 5 mm occurred 33 times and occupied about 73.7% in all the statistical events. However, only 7 events were associated with runoff depth larger than 10 mm, accounting for about 15.6% of the total events. The flood variability varied from 5.09 to 107.18 with an average of 22.44, and 80% of the statistical events were associated with flood variability less than 30.

Tab. 1 Statistic features of flood events from Shejiagou watershed (1961—1969)

Variables	Statistical description				
	Min.	Max.	Mean	Std. Dev.	CV
T/min	180	1 680	638	370.69	0.58
T_p/min	12	481	93.6	128.11	1.37
T_r/min	165	1 500	544	317.07	0.58
q_p/($m^3 \cdot s^{-1}$)	0.13	95.00	15.98	23.07	1.44
H/mm	0.20	30.70	5.40	6.94	1.29
q_m/($m^3 \cdot s^{-1}$)	0.02	4.77	0.74	1.05	1.43
FV	5.09	107.18	22.44	19.94	0.89
M_S/($t \cdot km^{-2}$)	0.48	19 254.80	3 495.65	4 952.98	1.42
S_m/($kg \cdot m^{-3}$)	2.62	827.94	538.98	203	0.38
S_{max}/($kg \cdot m^{-3}$)	12.60	953.0	680.04	217.47	0.32
SCV	1.06	5.92	1.48	0.88	0.59

Event based area-specific sediment yield varied from 0.48 t/km^2 to 19 254.8 t/km^2 with an average of 3 495.65 t/km^2. Totally 35 events were associated with area-specific sediment yield less than 3 500 t/km^2, occupying about 77.8% in all the examined events. However, only a tiny fraction (11.1%) of these events produced area-specific sediment yield larger than 10 000 t/km^2. The mean suspended sediment concentration averaged 538.98 kg/m^3 with a range of 2.62 ~ 827.94 kg/m^3. A large proportion (73.3%) of the events produced mean suspended sediment concentration exceeding 500 kg/m^3. However, only 5 events were associated with suspended sediment concentration less than 300 kg/m^3. Maximum suspended sediment concentration ranged from 12.6 kg/m^3 to 953 kg/m^3 with an average of 680.04 kg/m^3. A large proportion (77.8%) of the events was associated with maximum suspended sediment concentration exceeding 600 kg/m^3. However, only 4 events produced maximum suspended sediment concentration less than 300 kg/m^3.

In terms of coefficient of variation, the coefficient of variation of flood peak discharge and runoff depth was larger than that of mean and maximum suspended sediment concentration. This indicated that the variability of flood flows was relatively high and the variability of sediment delivery was relatively low. The coefficient of variation of flood variability (FV) was larger than that of suspended sediment concentration. This revealed that the flood hydrographs fluctuated and sediment exported smoothly.

Correlation coefficients presented in Tab. 2 shows that M_S is significantly correlated with H, q_p, q_m, FV, respectively ($P < 0.01$). Individually, M_S is linearly dependent on H with the maximum correlation coefficient of 0.99. This implies that flood runoff depth is indicative of the potential of single sediment-producing event, in that runoff depth is regarded as a comprehensive reflection of surface runoff generation and confluence. S_m and S_{max} are logarithmically correlated with q_p with correlation coefficient being 0.85 and 0.78, respectively ($P < 0.01$). SCV is negatively correlated to q_p with correlation coefficient being −0.72 for power regression ($P < 0.01$). This implies that flood peak discharge indicates the capacity of flood flow to deliver eroded sediments, and is the major driving force to induce suspended sediment concentration variability. Tab. 2 also indicates that the flood duration longer, the event-based flood variability highert ($P < 0.01$). Taken full into consideration, T, H, and q_p are selected as basic grouping indicators to generalize the event-based characteristics of flood flows. The flood events are then divided into different regimes.

Tab. 2 Correlation coefficients for simple regression among feature variables related to runoff and suspended sediment delivery from Shejiagou watershed

	T	q_p	H	q_m	FV	M_S	S_m	S_{max}	SCV
T	1								
q_p	0.1	1							
H	0.30 *	0.93 a **	1						
q_m	−0.22	0.89 a **	0.90 a **	1					
FV	0.50 **	0.64 a **	0.46 a **	−0.03	1				
M_S	0.26	0.92 **	0.99 **	0.88 a **	0.48 a **	1			
S_m	−0.01	0.85 b **	0.73 b **	0.77 b **	0.53 b **	0.89 a **	1		
S_{max}	0.03	0.78 b **	0.69 b **	0.70 b **	0.49 b **	0.88 a **	0.99 a **	1	
SCV	0.08	−0.72 a **	−0.61 a **	−0.68 a **	−0.40 a **	−0.83 a **	−0.91 a **	−0.83 a **	1

Note: * means correlation was significant at 0.05 level (2-tailed), ** means correlation was significant at 0.01 level (2-tailed). a means power regression; b means linear logarithm regression; coefficients without identification were derived from linear regression.

3.2 Intra-event-based flood regimes

Based on numerous trials and errors as well as result examination, a combined method of K-mean clustering and discriminant analysis was used to classify the flood events. Fisher's discriminant function was used in the discriminant analysis to determine the most suitable clusters. The equations for Fisher's discriminant functions are listed as follows.

$$F_1 = 0.008T + 0.004q_p - 0.052H - 4.917$$
$$F_2 = 0.066q_p - 0.101H - 0.697$$

The classification function equations used for classifications of different flood regimes are given as below.

$$D_1 = 0.101T + 0.119q_p - 0.761H - 80.293$$
$$D_2 = 0.056T + 0.074q_p - 0.441H - 25.351$$
$$D_3 = 0.025T + 0.066q_p - 0.256H - 6.135$$

The clustering results are shown in Fig. 2. The 45 recorded flood events were classified into three regimes (Tab. 3); the scatters of discrimination functions for different regimes are relatively gathered, implying that the classifications of flood regimes are relatively reasonable.

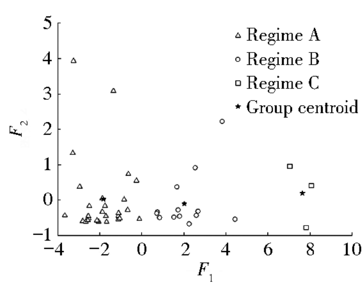

Fig. 2 Result of discriminant analysis on flood regimes

Specifically, Regime A, which is characterized by its shortest duration, least runoff depth, lowest flood variability, and moderate flood crest, is the most common regime of the highest frequency (62.2% of all the events). Regime B comprises flood events with medium duration, moderate runoff depth, medium flood variability, and least flood crest, and is of medium frequency (31.1% of all the events). Regime C is mainly clustered from flood events that are characterized by their longest duration, largest runoff depth, highest flow variability, and largest flood crest, and has the lowest frequency (6.7% of all the events).

The contribution of accumulative total runoff depth induced by different flood regimes to the summed runoff depth of all of the examined 45 events is 53%, 34% and 13% for Regimes A, B, and C, respectively. Flood duration, flood runoff depth, and flood peak discharge under different flood regimes are ranked in the following orders: T, C > B > A; H, C > A > B; q_p, C > A > B, respectively. Variance analysis shows that flood duration by different regimes are significantly different ($P < 0.001$), and regime-based flood peak discharge and runoff depth are not statistically different ($P > 0.3$). This indicates that flood regimes at Shejiagou catchment are mainly determined by time durations of individual flood events.

Tab. 3 Main statistic features of runoff and suspended sediment delivered by different flood regimes

Flood regime/ number of events	Statistical features										
	T/min	T_p/min	T_r/min	q_p/ ($m^3 \cdot s^{-1}$)	H/mm	q_m/ ($m^3 \cdot s^{-1}$)	FV	M_S/ ($t \cdot km^{-2}$)	S_m/ ($kg \cdot m^{-3}$)	S_{max}/ ($kg \cdot m^{-3}$)	SCV
A/28	405	41	364	16.3	4.6	0.9	16.9	3 071	571	707	1.3
B/14	894	163	731	14.1	5.9	0.4	27.9	3 676	448	600	2.0
C/3	1 617	265	1 349	22.1	10.2	0.5	49.2	6 618	664	802	1.2

3.3 Flood regime induced sediment delivery

The contribution of accumulative total sediment yield induced by different flood regimes to the summed sediment output of all the examined 45 events is 54%, 32%, and 13% for Regimes A, B, and C, respectively. This indicates that major sediment-producing events are derived from Regime C. Area-specific sediment yield, mean suspended sediment concentration and maximum suspended sediment concentration driven by different flood regimes are ranked in the following orders: M_S, C > B > A; S_m, C > A > B; S_{max}, C > A > B. Flood regime is indicative of runoff erosivity dynamics in eroding soil and transporting sediments. The flood regime based effect on soil erosion and sediment yield can be decomposed into at least two parts, i.e., regulation of flood runoff amount (depth), and alteration of runoff-sediment relationship[3]. Variance analysis shows that no significant difference is found for sediment yield, mean suspended sediment concentration, and maximum suspended sediment concentration between different flood regimes ($P > 0.1$). This indicates that limited influence caused by flood regime is exerted on the alteration of runoff-sediment relationship at Shejiagou watershed scale. The difference in event sediment yield driven by different flood regimes is mainly derived from the variations in flood runoff amount (depth).

To further quantify the influence of different flood regimes on event-based M_S, 16 events with M_S larger than 1 t/km^2 were selected to conduct comparative analyses on flood regime-based M_S derived from the same flood runoff amount (depth). Eight comparable groups were established in the analyses. Group-specific average flood runoff depth ranged from 2.4 mm to 23 mm and standard deviation varied from 0.004 mm to 0.16 mm with variation coefficient ranging from 0.1% to 7%. The number of comparable groups for Regimes B – A and C – A was 7 and 1, respectively. Relative M_S (the ratio of event-based M_S by Regimes B, C to that by Regime A) driven by the same flood runoff amount (depth) was then calculated under different flood regimes.

Fig. 3 illustrates relative M_S induced by the same flood runoff amount (depth) under different flood regimes. The ratio of area-specific sediment yield by different flood regimes is A∶B∶C = 1∶0.93∶1.22. Given that the flood runoff depth remains invariant, Regime C produces the most sediment, and Regime B produces the least sediment. Compared with Regime A, Regime B is associated with 7% decrease in event-based M_S. However, Regime C results 22% increase in event-based M_S. This indicates that flow-sediment relationships tend to be stable at watershed scale. As a result, limited variations in sediment export are caused by the alteration of flow-sediment relationships under the conditions of event flood runoff amount remaining the same.

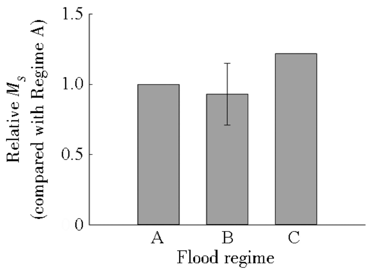

Fig. 3 Relative area-specific sediment yield driven by different flood regimes

3.4 Sediment flow behavior driven by flood regimes

To determine the effect of flood regime on sediment flow behavior, major process-specific variables for flood flows were selected to discriminate main driving forces for suspended sediment concentration dynamics under different flood regimes and different flood phases (rising limb and recession limb). The selection of process-specific parameters for flood flows mainly referred to the results obtained for runoff regime classification at the entire slope scale[3]. Flow-sediment relationships underlie different flood regimes were then established through multiple stepwise regressions with SPSS software.

Results presented in Tab. 4 show that variations in suspended sediment concentration are mainly driven by flood hydrographs. The best fitting equations are generally expressed in the linear-logarithmic forms of $S = a\ln q + b$ (S is suspended sediment concentration, kg/m^3; q is instantaneous water discharge, m^3/s), which are similar to previous studies[12]. The coefficients of determination of regression equations vary from 0.69 to 0.76. The regression parameter a, and b does not vary vastly: event-based equation with a being 94.1 ~ 110.2 and b being 447 ~ 505; rising limb with a being 84.8 ~ 108.1 and b being 384 ~ 447; recession limb with a being 101.4 ~ 118.6 and b being 486 ~ 559. It is obvious that composite indicators indicative of multi-factor functions in eroding and transporting sediments are not capable of improving the effectiveness of regression equations. This implies that instantaneous water discharge determines the runoff erosivity and is the major driving factor to induce sediment dynamics in flood flows at the catchment scale. Apparently, the remaining factors are dependent flood flow conditions and the function of other driving factors than instantaneous water discharge is masked in sediment delivery at the catchment scale.

Tab. 4 Flow-sediment relationships under different flood regimes

Flood regime	Runoff-sediment relationship		
	Event-based	Rising limb	Recession limb
A	$S = 95.4\ln q + 496$ ($R^2 = 0.69, n = 416, P < 0.001$)	$S = 86.3\ln q + 403$ ($R^2 = 0.76, n = 139, P < 0.001$)	$S = 107.5\ln q + 556$ ($R^2 = 0.72, n = 277, P < 0.001$)
B	$S = 94.1\ln q + 447$ ($R^2 = 0.72, n = 242, P < 0.001$)	$S = 84.8\ln q + 384$ ($R^2 = 0.71, n = 86, P < 0.001$)	$S = 101.4\ln q + 486$ ($R^2 = 0.75, n = 156, P < 0.001$)
C	$S = 110.2\ln q + 505$ ($R^2 = 0.71, n = 68, P < 0.001$)	$S = 108.1\ln q + 447$ ($R^2 = 0.76, n = 30, P < 0.001$)	$S = 118.6\ln q + 559$ ($R^2 = 0.72, n = 38, P < 0.001$)

4 Discussion

Compared with the results obtained at the entire slope scale[3], flood regimes at Shejiagou catchment are not complicated. No significant differences in essence are found between different regimes except magnitudes of flood scale and flood duration. This result is highly dependent on hydro-geomorphologic features underlying basin surface. Influences of different flood regimes on sediment export are also of varying magnitudes. No significant differences are found for area-specific sediment yield, mean and maximum suspended sediment concentration between different flood regimes. Additionally, unlike unsteady regime-specific runoff-sediment relationships at the entire slope scale, response relationships of suspended sediment concentration to flood flows are in consistency under different regimes. This indicates that runoff-sediment relationships tend to be stable at the catchment scale, which has been extensively validated[32]. As a result, the control of total sediment output is limited by altering runoff-sediment relationship through the regulation of flood hydrograph at the basin outlet. The magnitude of sediment discharge is mainly determined by the total amount of flood runoff.

The decision of management strategies is mainly based on the characteristics of soil erosion and sediment production. Consequently, erosion control should be aimed at establishing steady runoff-sediment relationship at the entire slope scale. However, sediment control should be runoff-reduction oriented at the catchment scale. In consideration of maintaining basin water resource, desirable approaches should be capable of breaking up the stability of existing runoff-sediment relationship with the aim of reserving a certain amount of water resources. Thus, improved sediment flow behavior can be achieved through the regulation of event-based flood runoff and runoff-sediment relationship. The management of the Chabagou watershed started in 1970—1980, and benefits of runoff and sediment reduction initiated in 1970s. Wide implementation of grass and forest as well as terraced fields, especially the large-scale build-up of check dams, deeply affects physical properties of basin underlying surface. The reshaped erosion environments have changed the surface hydrological process, which certainly leads to the redistribution of runoff erosivity and erosive energy, and then governs sediment flow behavior at the basin outlet. Therefore, analyzing the effects of anti-erosion measures on flood regimes associated with their functions in sediment control will benefit a better clarification of the role of runoff regulation and utilization in ecological management at the catchment scale.

5 Conclusions

(1) Event-based flood duration, event flood runoff amount (depth), and flood peak discharge can be used to describe basic characteristics of flood events at small watershed scale. The 45 flood events occurred over the period of 1961—1969 were grouped into 3 flood regimes based on the 3 above indicators. Regime A results flood events of the highest frequency with moderate flood peak discharge, the shortest duration, and the least runoff depth. Regime B comprises flood events of moderate frequency with moderate duration, moderate runoff depth, moderate flood variability, and the least flood crest. Regime C is mainly clustered from flood events of the lowest frequency with the longest duration, largest runoff depth, the highest flood variability, and the largest flood crest. Event-based flood duration is the major influencing factor that determines the flood regimes at Shejiagou catchment.

(2) Runoff-sediment relationships by flood flow tend to be stable at the catchment scale. The response of suspended sediment concentration to flood flows under different flood regimes and flood phases (rising limb and recession limb) can be described with linear-logarithmic equations. Area-specific sediment yield, mean suspended sediment concentration, and maximum suspended sediment concentration show no significant difference between different flood regimes. The difference in sediment output induced by flood events of different regimes is mainly derived from the variation in total flood runoff.

(3) The influence of flood regime on sediment flow behavior is limited at the catchment scale. The ratio of area-specific sediment yield by different flood regimes is A∶B∶C = 1∶0.93∶1.22 under the condition of total flood runoff being the same. The increment in area-specific sediment yield reaches the maximum with an increase rate of 22%, if event-based duration increases 1.7 times.

References

[1] WEI W, CHEN L, FU B, et al. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China[J]. Journal of Hydrology, 2007, 335(3-4): 247-258.

[2] QIN Wei, ZUO Changqing, YAN Qinghong, et al. Regularity of individual rainfall soil erosion in bare slope land of red soil [J]. Transactions of the CSAE, 2015, 31(2): 124-132. (in Chinese)

[3] ZHANG Letao, LI Zhanbin, WANG Shanshan. Impact of runoff regimes on sediment yield and sediment flow behavior at slope scale[J]. Transactions of the CSAE, 2015, 31(20): 124-131. (in Chinese)

[4] FANG N, SHI Z, LI L, et al. The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed[J]. CATENA, 2012, 99(1): 1-8.

[5] ZHENG Fenli, BIAN Feng, LU Jia, et al. Effects of rainfall patterns on hillslope erosion with longitudinal ridge in typical black soil region of northeast China [J]. Transactions of the Chinese Society for Agricultural Machinery, 2016, 47(2): 90-97. (in Chinese)

[6] WEN Leilei, ZHENG Fenli, YANG Qingsen, et al. Effects of rainfall patterns on hillslope farmland erosion in black soil region of northeast China [J]. Journal of Hydraulic Engineering, 2012, 43(9): 1084-1091. (in Chinese)

[7] GUO Tingfu, DUAN Qiaofu. The theory of runoff regulation and control is the quintessence of soil and water

conservation[J]. Soil and Water Conservation in China, 2001(11): 1 – 5. (in Chinese)

[8] LI Huaiyou, GAO Jianling, ZHAO Ancheng. Study on multi-factor integrated treatment mode of soil and water conservation based on runoff control and regulation[C]// Collected papers on the 4th Young Scientist Forum in Chinese Hydraulic Engineering Society, 2008:425 – 428. (in Chinese)

[9] YAN Qinghong, YUAN Cuiping, LEI Tingwu, et al. Effect of rainstorm patterns and soil erosion control practices on soil and water loss in small watershed on Loess Plateau[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(2): 169 – 175. (in Chinese)

[10] PENG T, WANG S. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China[J]. CATENA, 2012, 90(1): 53 – 62.

[11] AN J, ZHENG F L, HAN Y. Effects of rainstorm patterns on runoff and sediment yield processes[J]. Soil Science, 2014, 179(6): 293 – 303.

[12] LI Z, Li P, HAN J, et al. Sediment flow behavior in agro-watersheds of the purple soil region in China under different storm types and spatial scales[J]. Soil and Tillage Research, 2009, 105(2): 285 – 291.

[13] ZHAO Xining, WU Pute, FENG Hao, et al. Study on rainfall and runoff regulation and regional effects of runoff conservation and sediment reduction[J]. Journal of Natural Disasters, 2014, 23(4): 46 – 53. (in Chinese)

[14] CHEN Weibin, LIU Shengyun, DONG Zengchuan. Optimized arrangement of soil and water conservation measures based on runoff regulation and control [J]. Yellow River, 2010, 32(3): 81 – 82. (in Chinese)

[15] ZHAO Kerong, CHEN Lihua, XIAO Yang. Measure system of runoff control in Loess Region[J]. Science of Soil and Water Conservation, 2008, 6(4): 94 – 99. (in Chinese)

[16] WU Shufang, WU Pute, SONG Weixiu, et al. Study on the outflow processes of slope regulated by works and its effects on overland flow and sediment reduction [J]. Journal of Hydraulic Engineering, 2010, 41(7): 870 – 875. (in Chinese)

[17] WU Shufang, WU Pute, YUAN Lifeng. Hydraulic characteristics of sheet flow with slope runoff regulation [J]. Transactions of the CSAE, 2010, 26(3): 14 – 19. (in Chinese)

[18] ZHANG Min, ZHANG Mingwu, HE Guiying, et al. Analysis of erosion efficiency in different flood wave type on non-floodplain flood in lower Yellow River [J]. Yellow River, 2016, 38(1): 1 – 4. (in Chinese)

[19] LI Zhanbin. Study on small watershed single storm erosion sediment yield in loess region[J]. Journal of Xi'an University of Technology, 1996, 12(3): 177 – 183. (in Chinese)

[20] LI Zhanbin, FU Suhua, XIE Jiancang, et al. A study on storm runoff sediment yield in Kuyehe river watershed [J]. Journal of Hydraulic Engineering, 1998(Supp. 1): 19 – 24. (in Chinese)

[21] ZHOU Peihua. Discussion on mechanism of loess erosion[J]. Research of Soil and Water Conservation, 1997, 4(5): 40 – 46. (in Chinese)

[22] WANG Siyuan, WANG Guangqian, CHEN Zhixiang. Relationship between land use and soil erosion in Yellow River Basin[J]. Journal of Natural Disasters, 2005, 14(1): 32 – 37. (in Chinese)

[23] GAO Zhaoliang, FU Yanling, ZHANG Jianjun, et al. Responses of streamflow and sediment load to vegetation restoration in catchments on the Loess Plateau [J]. Transactions of the CSAE, 2013, 29(6): 99 – 105. (in Chinese)

[24] FANG Haiyan, CAI Qiangguo, CHEN Hao, et al. Research on the dynamics of temporal sediment transport in a gullied loess basin: the lower Chabagou creek on the Loess Plateau[J]. Progress in Geography, 2007, 26(5): 77 – 87. (in Chinese)

[25] LIAO Yishan, ZHUO Muning, LI Dingqiang, et al. A GIS-based distributed soil erosion and sediment yield model for typical watersheds in hilly loess areas: a case study in Shejiagou catchment [J]. Journal of Sediment Research, 2012(1): 7 – 13. (in Chinese)

[26] CAI Qiangguo, LIU Jigen, LIU Qianjin. Research of sediment yield statistical model for single rainstorm in Chabagou drainage basin [J]. Geographical Research, 2004, 23(4): 433 – 439. (in Chinese)

[27] CUI Lingzhou, LI Zhanbin, GUO Yanbiao, et al. Fractal-information-dimension-based relationship between sediment yield and topographic feature of eatershed[J]. Acta Pedologica Sinica, 2007, 44(2): 197 – 203. (in Chinese)

[28] LIAO Yishan, CAI Qiangguo, ZHUO Muning, et al. Influence of channel networks on the sediment yield under variant temporal and spatial scales: a case study of Chabagou watershed [J]. Progress in Geography, 2009, 28(1): 47 – 54. (in Chinese)

[29] YANG Tao, ZHANG Ying, CHEN Jieren, et al. Study on distributed hydrologic model in Chabagou basin of Yellow River based on digital platform[J]. Journal of Hydraulic Engineering, 2005(4): 456 – 460. (in Chinese)

[30] CHEN Xiao'an, CAI Qiangguo, ZHENG Mingguo, et al. Empirical soil erosion model for single rainstorm in Chabagou drainage basin[J]. Progress in Geography, 2011, 30(3): 325 – 329. (in Chinese)

[31] FANG Haiyan, CAI Qiangguo, LI Qiuyan. Study on the runoff generation capacity of slope surface and its influencing factors in a hilly loess region on the Loess Plateau[J]. Geographical Research, 2009, 28(3): 583 – 591. (in Chinese)

[32] ZHENG M, LI R, HE J. Sediment concentrations in run-off varying with spatial scale in an agricultural subwatershed of the Chinese Loess Plateau [J]. Hydrological Processes, 2015, 29(26): 5414 – 5423.

[33] XU J. Erosion caused by hyperconcentrated flow on the Loess Plateau of China[J]. CATENA, 1999, 36(1 – 2): 1 – 19.

doi:10.6041/j.issn.1000-1298.2016.08.015

黄土丘陵沟壑区典型小流域不同洪水类型侵蚀输沙效应

张乐涛[1,2]　李占斌[1,3]　肖俊波[4]　王杉杉[1,2]

（1.中国科学院水利部水土保持研究所黄土高原土壤侵蚀与旱地农业国家重点实验室，陕西杨凌 712100；
2.中国科学院大学，北京 100049；3.西安理工大学西北水资源与环境生态教育部重点实验室，西安 710048；
4.西北农林科技大学水土保持研究所，陕西杨凌 712100）

摘要：不同降雨-径流格局下的土壤侵蚀响应是土壤侵蚀规律研究中的基本关系之一，以黄土丘陵沟壑区典型小流域岔巴沟的一级支沟蛇家沟为例，分析了不同洪水类型驱动下的小流域侵蚀输沙过程。以蛇家沟水文站1961—1969年记录的45次洪水事件为数据基础，选取洪水历时、次洪水径流深和洪峰流量作为洪水径流过程的特征指标，运用K均值聚类和判别分析相结合的方法，将全部洪水事件划分为3种类型。其中，A型洪水具有短历时、小径流、低变率和中洪峰的特点，是最为普遍的类型。B型洪水具有中历时、中径流、中变率和小洪峰的特点，发生频率居中。C型洪水具有长历时、大径流、高变率、大洪峰的特点，发生频率最低。洪水历时是决定洪水类型的主要因素。不同洪水类型下的输沙模数、平均含沙量及最大含沙量由大到小依次分别为：C、B、A；C、A、B；C、A、B；但其差异并不显著（$P>0.1$）。蛇家沟小流域的水沙关系趋于稳定，径流含沙量的变化可用流量的对数函数进行描述。在径流量保持一致的情况下，不同洪水类型驱动下的输沙模数相对大小（A∶B∶C）为1∶0.93∶1.22。当洪水历时延长1.7倍时，其增沙作用达到极大值，输沙模数最大增幅为22%。研究结果可为流域洪水类型划分、全面科学评估径流调控及利用的水土保持效益提供有益参考。

关键词：洪水类型；小流域；侵蚀产沙；径流调控

中图分类号：TV122；S157.1　　**文献标识码**：A　　**文章编号**：1000-1298(2016)08-0109-08

Effects of Different Flood Regimes on Soil Erosion and Sediment Transport in Typical Small Watershed of Loess Hilly－Gully Region

Zhang Letao[1,2]　Li Zhanbin[1,3]　Xiao Junbo[4]　Wang Shanshan[1,2]

（1. *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau*, *Institute of Soil and Water Conservation*, *Chinese Academy of Sciences*, *Ministry of Water Resources*, *Yangling*, *Shaanxi* 712100, *China*
2. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*
3. *Key Laboratory of Northwest Water Resources and Environment Ecology*, *Ministry of Education*, *Xi'an University of Technology*, *Xi'an* 710048, *China*
4. *Institute of Soil and Water Conservation*, *Northwest A&F University*, *Yangling*, *Shaanxi* 712100, *China*）

Abstract: Soil erosion responses under different rainfall and runoff patterns are fundamentals for the studies of soil erosion mechanisms. To investigate the influence of flood regimes on soil erosion and sediment yield at small watershed scale, a typical small watershed—Shejiagou catchment was selected to conduct data collection and analysis, and Shejiagou is a first order tributary of Chabagou drainage basin lying in the hilly and gully region of Chinese Loess Plateau. Based on 45 individual flood events recorded at Shejiagou Hydrological Station during 1961 to 1969, all the flood events were categorized into three regimes through a combined approach of K-mean clustering and discriminant analysis with three grouping variables, including flood duration, event flood runoff depth and peak discharge. Regime A was

收稿日期：2015－12－09　修回日期：2016－03－03
基金项目：国家自然科学基金重点项目(41330858)
作者简介：张乐涛(1989—)，男，博士生，主要从事土壤侵蚀与水土保持研究，E-mail: zhangletao10@mails.ucas.ac.cn
通信作者：李占斌(1962—)，男，教授，博士生导师，主要从事土壤侵蚀与水土保持研究，E-mail: zbli@ms.iswc.ac.cn

characterized by short duration, small flood runoff depth, low flood variability and medium peak discharge, which was the most common regime. Regime B was featured with medium duration, medium flood runoff depth, medium flood variability and small peak discharge, which was of medium frequency. Regime C mainly included flood events of long duration, large runoff depth, high variability, as well as large peak discharge, which was of the lowest frequency. The regime of flood events was mainly controlled by flood duration at the studied scale. Area-specific sediment yield, mean suspended sediment concentration and maximum suspended sediment concentration driven by different flood regimes can be ranked in the order of C > B > A, C > A > B, C > A > B, respectively. However, no significant difference was found among the three flood regimes for the variables examined ($P > 0.1$). The runoff-sediment relationship was relatively constant at Shejiagou watershed, the variations in suspended sediment concentration can be well described by the logarithmic function of instantaneous discharge. The sediment output at watershed outlet was mainly controlled by event-based total flood runoff. Given that event flood runoff depth was kept constant, the ratio of area-specific sediment yield driven by different flood regimes (A∶B∶C) was 1∶0.93∶1.22. If the flood duration was increased by 1.7 times, the flood regime-based increase for sediment yield reached the maximum, and the maximum increase rate for area-specific sediment yield was 22%. The results may provide beneficial evidence for categorization of individual flood events, and overall rational-based evaluation on the soil and water conservation benefits brought by runoff regulation systems at watershed scale.

Key words: flood regime; small watershed; soil erosion and sediment yield; runoff regulation

引言

降雨及地表径流的时空分布特征影响了侵蚀动力及能量的时空分配格局,在坡面及流域不同尺度的侵蚀输沙过程中发挥着重要作用[1-6]。降雨径流调控及利用是实施坡面及沟道治理措施、重塑协调水沙关系的基本原则和重要依据[7-8]。辨析不同降雨及径流类型条件下的侵蚀输沙响应及水沙关系演变特征有利于深刻阐释区域水土流失规律,能够促进水土保持措施的合理规划及其因时因地制宜的实施[2,9-12]。近年来,坡面径流调控的水土保持效应及其作用机制、基于径流调控的水土保持措施优化配置等方面的研究已取得重要进展[13-17],在完善水土保持综合治理措施的生态水文功能评价、提升流域的综合治理水平等方面产生了积极的影响。目前,虽有相关研究涉及洪水过程调控的调沙效应分析[18],不同洪水类型对流域侵蚀输沙过程的影响却尚未得到完全揭示,水土保持措施对径流格局及其侵蚀产沙响应的调节作用也需进一步澄清。

黄土高原地区,暴雨洪水径流是流域侵蚀输沙的主要驱动因素之一[19-20],土壤侵蚀极其严重。鉴于该区土壤侵蚀多由少数几场暴雨引起的特殊性[21-22]及水土保持措施调控地表径流而不能调节径流年内分配的局限性[23],水土保持措施对次洪水过程时空尺度效应的调节作用成为控制流域泥沙输出的关键。因此,分析不同洪水类型下的水沙过程、系统揭示流域侵蚀输沙对不同洪水类型的响应关系有助于深入阐明径流调控及利用的水土保持意义,可为明确水土保持措施对流域水文泥沙时空过程的调控效应奠定基础,并进一步推动基于径流调控的流域水土保持措施治理效益的精细化评估。

黄土高原丘陵沟壑区沟壑纵横,侵蚀地貌独特,次暴雨洪水侵蚀事件极具典型性和代表性。该区岔巴沟流域水文测站齐全,自建站始积累了丰富的实测水文泥沙资料,是开展水沙关系演变研究的理想场所[24-25];其对于流域暴雨产沙模型构建、泥沙传输时空尺度效应、水文模拟及地貌过程等方面的研究具有重要意义[26-29]。本文以该流域典型支沟蛇家沟小流域为例,以1961—1969年的实测水文泥沙资料为基础,基于数理统计分析划分小流域尺度次暴雨条件下基于事件的洪水类型并分析其对侵蚀输沙过程的影响,以期进一步丰富径流调控理论的基本内涵,并为水土保持综合治理措施的优化配置及其生态水文效益的全面评估、提升流域生态治理水平提供理论依据。

1 研究区概况

子洲径流实验站位于陕西省子洲县境内的岔巴沟流域,建于1958年,于1969年撤消。岔巴沟位于北纬37°31′、东经109°47′,流域面积为205 km^2,海拔高度为900~1 100 m,沟道长26.5 km。曹坪站以上集水面积187 km^2,流域形状基本对称,沟长

24.1 km，流域平均宽度 7.22 km，沟道密度 1.05 km/km^2。该区属于半干旱区，1959—1969 年多年平均降水量为 480 mm，降水季节分配极不均匀，70% 集中在 6—9 月份，且多为短历时、高强度暴雨，最大降雨强度为 3.5 mm/min。径流年内分配极不均匀，62% 集中于 7—9 月份，年平均温度约 8℃，最高气温 38℃，最低气温 -27℃，霜冻期约半年。

本区土壤以黄土母质发育的黄绵土为主，大于 0.05 mm 的土壤颗粒约占 25.8%，0.01 ~ 0.05 mm 之间的土壤颗粒约占 57.7%，小于 0.01 mm 的土壤颗粒约占 16.5%[30]。土壤颗粒中以粉粒为主，土质疏松，孔隙度大，极易被侵蚀。1954—1958 年的年侵蚀模数为 6 267 ~ 23 670 t/km^2，平均为 15 780 t/km^2。该流域植被覆盖率低，具有典型旱地农业特征，在 1959—1969 年处于人为干扰较少的近自然状态，植被覆盖、作物类型及其种植方式对坡面产流能力及径流含沙量的影响有限且并无较大变化[31-32]，本文暂不考虑其侵蚀输沙效应。蛇家沟为岔巴沟流域的一级支沟，流域面积为 4.72 km^2，流域长度为 4.5 km，平均宽度为 1.05 km，沟道平均比降为 1.15%，集水区平均坡度为 44.7%，平均高程为 1 037 m。水文站与河口距离为 0.2 km，施测期间控制面积略有调整，1961—1964 年 5 月，为 4.72 km^2；1964 年 7 月—1969 年，为 4.26 km^2，研究区位置如图 1 所示。

图 1　研究区位置

Fig. 1　Location of study area

2　数据来源与研究方法

本文所采用的水文泥沙数据来源于黄河水利委员会子洲径流实验站水文实验资料（1959—1969 年）。岔巴沟流域内共设 9 处水文站，嵌套分布，观测全流域径流、泥沙过程；布设雨量站 45 处，均匀分布，观测流域降雨过程；由自记雨量计记录降雨过程，测流建筑物为三角测流槽，详细观测径流过程，所有水沙数据包括水位、流量、含沙量和输沙量等的测量及采样和实验分析均严格按照国际标准进行[33]。

根据水文站相关测验标准[32]，将径流深大于 0.05 mm、洪峰流量大于 0.1 m^3/s、历时超过 150 min 的汛期径流事件定义为一次洪水事件。查阅子洲径流实验站水文实验资料（1959—1969 年）中的汛期水文要素过程表和洪水特征值统计表可知，蛇家沟水文站 1961—1969 年间共记录洪水、泥沙过程 45 次。其中，输沙模数小于 1 t/km^2 的事件 1 次，分析过程采用记录的全部事件，而未将其剔除。在简单回归分析径流与输沙关系的基础上，筛选指示基于事件的径流及输沙特征的合理指标。基于径流特征指标，综合采用聚类分析、判别分析的方法对洪水事件进行归类，划分不同的洪水类型，分析不同洪水类型驱动下的侵蚀输沙特征。最后，利用径流相关特征指标通过回归分析构建水沙关系，对不同洪水类型下的含沙量过程进行描述，解析雨洪侵蚀条件下含沙量过程的形成原因。

以洪水历时（T）、涨水历时（T_p）、落水历时（T_r）、洪峰流量（q_p）、径流量（H）、平均流量（q_m）、洪水变率（洪峰流量与平均流量的比值，FV）等指标反映基于事件的洪水径流特征；以输沙模数（M_S）、平均含沙量（S_m）、最大含沙量（$S_{\max}$）和含沙量变率（最大含沙量与平均含沙量之比，SCV）等指标反映基于事件的侵蚀输沙特征。聚类分析、相关分析和回归分析等数据分析过程使用 SPSS 18.0，绘图使用 SigmaPlot 12.5。

3　结果分析

3.1　基于事件的洪水径流侵蚀输沙特征

统计结果（表 1）表明，在 1961—1969 年，蛇家沟洪水事件的各项指标变化范围均较大。次洪水事件的洪水历时变化范围为 180 ~ 1 680 min，平均为 638 min。其中，历时超过 1 000 min 的洪水事件共 6 次，占全部洪水事件的 13.3%；历时小于 600 min 的洪水事件共 28 次，占全部洪水事件的 62.2%。洪峰流量的变化范围为 0.13 ~ 95 m^3/s，平均为 15.98 m^3/s。其中，洪峰流量小于 16 m^3/s 的洪水事件共 33 次，占全部洪水事件的 73.3%；洪峰流量大于 30 m^3/s 的洪水事件共 6 次，占全部洪水事件的 13.3%。径流量最小为 0.2 mm，最大为 30.7 mm，平均为 5.4 mm。其中，径流量小于 5 mm 的洪水事件共 33 次，占全部洪水事件的 73.3%；径流量大于 10 mm 的洪水事件共 7 次，占全部洪水事件的 15.6%。洪水变率的变化范围为 5.09 ~ 107.18，平均为 22.44，洪水变率小于 30 的洪水事件共 36 次，

占全部径流事件的80%。

表1 蛇家沟洪水事件统计特征(1961—1969年)

Tab.1 Statistic features of flood events from Shejiagou watershed (1961—1969)

参数	最小值	最大值	平均值	标准差	变异系数
T/min	180	1 680	638	370.69	0.58
T_p/min	12	481	93.6	128.11	1.37
T_r/min	165	1 500	544	317.07	0.58
q_p/($m^3 \cdot s^{-1}$)	0.13	95.00	15.98	23.07	1.44
H/mm	0.20	30.70	5.40	6.94	1.29
q_m/($m^3 \cdot s^{-1}$)	0.02	4.77	0.74	1.05	1.43
FV	5.09	107.18	22.44	19.94	0.89
M_S/($t \cdot km^{-2}$)	0.48	19 254.80	3 495.65	4 952.98	1.42
S_m/($kg \cdot m^{-3}$)	2.62	827.94	538.98	203	0.38
S_{max}/($kg \cdot m^{-3}$)	12.60	953.0	680.04	217.47	0.32
SCV	1.06	5.92	1.48	0.88	0.59

次洪水事件输沙模数的变化范围为0.48 ~ 19 254.80 t/km^2,平均为3 495.65 t/km^2。其中,输沙模数小于3 500 t/km^{2}的洪水事件共35次,占全部洪水事件的77.8%;输沙模数大于10 000 t/km^{2}的洪水事件共5次,占全部洪水事件的11.1%。平均含沙量的变化范围为2.62 ~ 827.94 kg/m^3,平均为538.98 kg/m^3。其中,平均含沙量小于300 kg/m^{3}的洪水事件仅5次,占全部洪水事件的11.1%;大于500 kg/m^{3}的洪水事件共33次,占全部洪水事件的73.3%。最大含沙量的变化范围为12.6 ~ 953 kg/m^3,平均为680.04 kg/m^3。其中,最大含沙量小于300 kg/m^{3}的洪水事件仅4次,占全部洪水事件的8.9%;大于600 kg/m^{3}的洪水事件共35次,占全部洪水事件的77.8%。

洪峰流量、径流量的变异系数大于平均含沙量、最大含沙量的变异系数,表明洪水事件的变异程度较高,而侵蚀输沙事件的变异程度则相对较低。洪水变率的变异系数大于含沙量变率的变异系数,表明洪水径流过程波动性较高,而侵蚀输沙过程则较为平稳。

表2的结果显示,H、q_p、q_m、FV与M_S均显著相关($P<0.01$),是影响洪水径流侵蚀输沙的重要因素。其中,M_S与H呈线性征相关,相关系数最大,为0.99。表明作为流域地表产汇流综合信息的反映,径流量可以表征地表径流潜在的侵蚀产沙能力。S_m、S_{max}、SCV与q_p、q_m、H、FV均显著相关($P<0.01$)。其中,S_m、S_{max}与q_p关系最为密切,呈对数函数关系,相关系数分别为0.85和0.78;SCV与q_p呈幂函数负相关关系,相关系数为-0.72。表明洪峰流量可以表征洪水径流挟沙能力的变化,是造成含沙量变率的主要因素。表2同时表明,洪水历时越长,次洪水事件变率越大($P<0.01$)。因此,综合选取T、H和q_p 3个指标综合表征蛇家沟洪水径流基本特征。

表2 蛇家沟径流与输沙特征变量的简单回归相关系数

Tab.2 Correlation coefficients for simple regression among feature variables related to runoff and suspended sediment delivery from Shejiagou watershed

	T	q_p	H	q_m	FV	M_S	S_m	S_{max}	SCV
T	1								
q_p	0.1	1							
H	0.30*	0.93a**	1						
q_m	-0.22	0.89a**	0.90a**	1					
FV	0.50**	0.64a**	0.46a**	-0.03	1				
M_S	0.26	0.92**	0.99**	0.88a**	0.48a**	1			
S_m	-0.01	0.85b**	0.73b**	0.77b**	0.53b**	0.89a**	1		
S_{max}	0.03	0.78b**	0.69b**	0.70b**	0.49b**	0.88a**	0.99a**	1	
SCV	0.08	-0.72a**	-0.61a**	-0.68a**	-0.40a**	-0.83a**	-0.91a**	-0.83a**	1

注:* 在$P<0.05$水平显著相关(双侧),**在$P<0.01$水平显著相关(双侧)。a幂函数回归,b对数函数回归,无字母标记的为线性回归。

3.2 洪水类型

以45场次洪水径流事件为统计样本,T、H和q_p作为分类变量对洪水事件进行分组。经反复试错和结果检验,综合使用K均值聚类和判别分析对洪水事件进行分类。

判别分析采用Fisher判别函数,判别函数分别为

$$F_1 = 0.008T + 0.004q_p - 0.052H - 4.917$$

$$F_2 = 0.066q_p - 0.101H - 0.697$$

不同洪水类型的分类函数分别为

$$D_1 = 0.101T + 0.119q_p - 0.761H - 80.293$$

$$D_2 = 0.056T + 0.074q_p - 0.441H - 25.351$$

$$D_3 = 0.025T + 0.066q_p - 0.256H - 6.135$$

聚类结果见图2。全部洪水事件被划分为3类(表3),不同洪水类型判别函数的散点图均较为聚集,表明分类结果较为合理。

在3种洪水类型中,A型洪水历时最短、径流深最小、洪水变率最低、洪峰流量居中、发生频率最高,其事件数占全部洪水事件的62.2%。B型洪水具

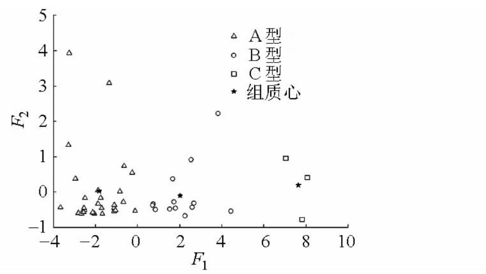

图 2　洪水类型判别分析结果

Fig. 2　Result of discriminant analysis on flood regimes

有中历时、中径流、中变率、洪峰流量最小的特点，发生频率居中，其事件数占全部洪水事件的 31.1%。

C 型洪水发生频率最低，其洪水事件的历时最长、径流深最大、洪水变率最高、洪峰流量最大，事件数仅占全部洪水事件的 6.7%。

各类型洪水累积径流量占全部洪水事件总径流量的比例依次为 A(53%)、B(34%)、C(13%)。各洪水类型主要径流特征值由大到小依次为：T：C、B、A；H：C、B、A；q_p：C、A、B。方差分析结果显示，不同类型的洪水事件洪水历时具有显著性差异($P<0.001$)，而洪峰流量和径流深受洪水类型的影响较小($P>0.3$)，表明蛇家沟小流域的洪水类型主要取决于洪水事件的时间尺度。

表 3　不同洪水类型的主要径流及侵蚀输沙统计特征

Tab. 3　Main statistic features of runoff and suspended sediment delivered by different flood regimes

洪水类型/事件数	主要统计特征										
	T/min	T_p/min	T_r/min	q_p/($m^3 \cdot s^{-1}$)	H/mm	q_m/($m^3 \cdot s^{-1}$)	FV	M_S/($t \cdot km^{-2}$)	S_m/($kg \cdot m^{-3}$)	S_{max}/($kg \cdot m^{-3}$)	SCV
A/28	405	41	364	16.3	4.6	0.9	16.9	3 071	571	707	1.3
B/14	894	163	731	14.1	5.9	0.4	27.9	3 676	448	600	2.0
C/3	1 617	265	1 349	22.1	10.2	0.5	49.2	6 618	664	802	1.2

3.3　不同洪水类型下的输沙特征

不同洪水类型驱动下的累积输沙量占全部洪水事件总输沙量的比例依次为 A(54%)、B(32%)、C(13%)。各洪水类型主要输沙特征值由大到小依次为：M_S：C、B、A；S_m：C、A、B；S_{max}：C、A、B。不同的洪水类型反映了不同的侵蚀动力条件，其对侵蚀输沙过程的影响至少包含调节洪水径流量和改变水沙关系两方面[3]。方差分析结果显示，不同类型洪水事件的输沙量、平均含沙量及最大含沙量之间均无显著性差异($P>0.1$)。该结果表明在蛇家沟小流域尺度下，洪水类型对水沙关系的影响有限，不同类型的洪水事件输沙量的差异可能主要来源于洪水径流量的改变。

为确定相同径流深条件下不同洪水类型的侵蚀产沙效应，筛选 16 次输沙模数大于 1 t/km^2 的洪水事件，共构建 8 个对比组，进行不同洪水类型间的对比分析。其中，A 型与 B 型洪水对比组 7 个，A 型与 C 型洪水对比组 1 个，参与对比的洪水事件径流深变化范围为 2.4 ~ 23 mm，标准差控制在 0.004 ~ 0.16 mm，变异系数控制在 0.1% ~ 7%。以 A 型洪水为基准，分别计算不同洪水类型在相同径流量条件下的相对输沙模数(B、C 型洪水事件输沙模数与 A 型洪水事件输沙模数的比值)。

相同径流深条件下，不同类型洪水事件驱动的平均输沙模数之比(A∶B∶C)为 1∶0.93∶1.22(图 3)；相应的平均洪水历时比(A∶B∶C)为 1∶2.3∶2.7。与 A 型洪水相比，B 型洪水输沙模数平均减少 7%，C 型洪水输沙模数平均增大 22%。表明流域尺度的水沙关系趋于稳定。在次洪水径流量相同的条件下，不同洪水类型间由水沙关系改变引起的输沙效应有限。

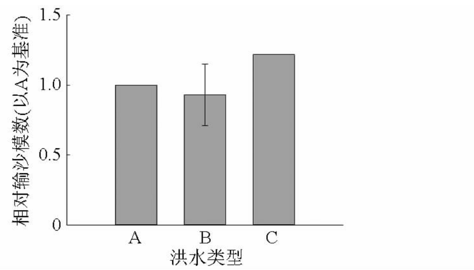

图 3　不同类型洪水事件的相对输沙模数

Fig. 3　Relative area-specific sediment yield driven by different flood regimes

3.4　不同洪水类型下的水沙传递关系

为明确不同洪水类型对水沙关系的影响，选取与主要洪水特征相关的过程参数，通过 SPSS 进行多元逐步回归分析，筛选不同洪水类型和洪水阶段(涨水和落水)控制含沙量变化的主要因素，构建雨洪侵蚀条件下蛇家沟小流域的水沙间的传递关系，基于洪水径流过程的参数筛选主要参考全坡面尺度径流类型划分结果[3]。

表 4 的结果反映蛇家沟小流域不同类型洪水事件含沙量的变化主要受洪水径流过程的驱动，最优回归方程均符合 $S=a\ln q+b$ 的形式(S 为含沙量，kg/m^3；q 为流量，m^3/s)，与部分研究结果类似[12]。其中，决定系数 R^2 为 0.69 ~ 0.76。回归参数 a、b 的

表4 不同洪水类型下的水沙响应关系

Tab. 4 Flow-sediment relationships under different flood regimes

洪水类型	水沙响应关系		
	综合	涨水段	落水段
A	$S=95.4\ln q+496$ ($R^2=0.69, n=416, P<0.001$)	$S=86.3\ln q+403$ ($R^2=0.76, n=139, P<0.001$)	$S=107.5\ln q+556$ ($R^2=0.72, n=277, P<0.001$)
B	$S=94.1\ln q+447$ ($R^2=0.72, n=242, P<0.001$)	$S=84.8\ln q+384$ ($R^2=0.71, n=86, P<0.001$)	$S=101.4\ln q+486$ ($R^2=0.75, n=156, P<0.001$)
C	$S=110.2\ln q+505$ ($R^2=0.71, n=68, P<0.001$)	$S=108.1\ln q+447$ ($R^2=0.76, n=30, P<0.001$)	$S=118.6\ln q+559$ ($R^2=0.72, n=38, P<0.001$)

变化范围均不大：综合过程：a 为 94.1～110.2，b 为 447～505；涨水段：a 为 84.8～108.1，b 为 384～447；落水段：a 为 101.4～118.6，b 为 486～559。反映多因素综合作用的复合指标并不能提高回归方程的有效性，表明瞬时流量是决定该尺度洪水径流输沙动力的主导因素，其余因素皆处于从属地位，其在流域输沙过程中的作用被掩盖。

4 讨论

与该区全坡面尺度相比[3]，蛇家沟小流域尺度的洪水类型并不复杂，不同洪水类型之间除洪水历时外，只有规模大小，不存在本质区别。这与流域下垫面水文、地貌条件（产汇流状况）有关。不同洪水类型的侵蚀输沙效应也只存在量级大小之别，其对尺度的输沙模数、平均含沙量、最大含沙量均没有显著影响。此外，与全坡面尺度不稳定的水沙关系不同，蛇家沟不同洪水类型下含沙量对洪水径流的响应关系具有一致性，表明该尺度下的水沙关系趋于稳定，这与已有研究结果相一致[32]。因此，不同洪水过程通过改变水沙关系改变流域总泥沙输出的作用有限，输沙量的差异主要取决于洪水总径流量的变化。

侵蚀产沙特点是制定治理策略的重要依据。据此，全坡面尺度的侵蚀治理应致力于建立稳定的水沙关系，而小流域尺度的泥沙调控应以控制流域产水量为导向。理想的治理途径应当既能够维持一定规模的水资源总量，又能够打破流域既有水沙关系的稳定性，通过调节洪水事件的径流量和水沙传递关系控制流域尺度的泥沙输出。1970—1980年，岔巴沟流域处于初步规模治理阶段，水土保持措施发挥减水减沙效益始于20世纪70年代。林草措施、梯田措施的广泛实施，尤其是淤地坝的大规模建设，深刻影响了下垫面的物理特性，重塑了流域侵蚀环境，改变了流域地表水文过程，势必造成径流侵蚀能量和动力的重新分配，进而调控流域的泥沙输出过程。因此，分析20世纪70年代以后治理条件下水土保持措施对流域洪水类型的影响及其侵蚀输沙效应，对于进一步阐明径流调控利用的水土保持意义将具有重要的启示作用。

5 结论

（1）洪水历时、洪水总径流量及洪峰流量可用以描述小流域尺度洪水事件的基本特征。蛇家沟小流域1961—1969年45次洪水事件按以上3个指标可划分为3种不同洪水类型。其中，A型洪水洪峰流量居中，历时最短、径流深最小、发生频率最高；B型洪水具有中历时、中径流、中变率的特点，洪峰流量最小，发生频率次之；C型洪水发生频率最低，其洪水事件的历时最长、径流深最大、洪水变率最高、洪峰流量最大。洪水历时是影响蛇家沟小流域洪水类型的主要因素。

（2）雨洪侵蚀条件下蛇家沟小流域的水沙关系趋于稳定。不同洪水类型及洪水阶段（涨水段与落水段）含沙量对洪水径流过程的响应关系均可用对数函数进行描述，不同洪水类型驱动下的输沙模数、平均含沙量及最大含沙量并无显著差异，不同类型洪水事件输出泥沙量的差异主要来源于径流量的变化。

（3）蛇家沟流域水沙关系趋于稳定，不同洪水类型对流域侵蚀输沙过程的影响有限。洪水总径流量一致的情形下，不同洪水类型驱动的输沙模数的相对大小（A∶B∶C）为1∶0.93∶1.22。当洪水历时延长1.7倍时，其增沙作用达到极大值，输沙模数最大增幅为22%。

参考文献

1 WEI W, CHEN L, FU B, et al. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China[J]. Journal of Hydrology, 2007, 335(3-4): 247-258.

2 秦伟，左长清，晏清洪，等. 红壤裸露坡地次降雨土壤侵蚀规律[J]. 农业工程学报，2015，31(2)：124－132.
QIN Wei, ZUO Changqing, YAN Qinghong, et al. Regularity of individual rainfall soil erosion in bare slope land of red soil [J]. Transactions of the CSAE, 2015, 31(2): 124－132. (in Chinese)
3 张乐涛，李占斌，王杉杉. 坡面径流类型对侵蚀产沙及水沙传递关系的影响[J]. 农业工程学报，2015，31(20)：124－131.
ZHANG Letao, LI Zhanbin, WANG Shanshan. Impact of runoff regimes on sediment yield and sediment flow behavior at slope scale [J]. Transactions of the CSAE, 2015, 31(20): 124－131. (in Chinese)
4 FANG N, SHI Z, LI L, et al. The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed[J]. CATENA, 2012, 99(1): 1－8.
5 郑粉莉，边锋，卢嘉，等. 雨型对东北典型黑土区顺坡垄作坡面土壤侵蚀的影响[J]. 农业机械学报，2016，47(2)：90－97.
ZHENG Fenli, BIAN Feng, LU Jia, et al. Effects of rainfall patterns on hillslope erosion with longitudinal ridge in typical black soil region of northeast China [J]. Transactions of the Chinese Society for Agricultural Machinery, 2016, 47(2): 90－97. (in Chinese)
6 温磊磊，郑粉莉，杨青森，等. 雨型对东北黑土区坡耕地土壤侵蚀影响的试验研究[J]. 水利学报，2012，43(9)：1084－1091.
WEN Leilei, ZHENG Fenli, YANG Qingsen, et al. Effects of rainfall patterns on hillslope farmland erosion in black soil region of northeast China[J]. Journal of Hydraulic Engineering, 2012, 43(9): 1084－1091. (in Chinese)
7 郭廷辅，段巧甫. 径流调控理论是水土保持的精髓——四论水土保持的特殊性[J]. 中国水土保持，2001(11)：1－5.
GUO Tingfu, DUAN Qiaofu. The theory of runoff regulation and control is the quintessence of soil and water conservation[J]. Soil and Water Conservation in China, 2001(11): 1－5. (in Chinese)
8 李怀有，高健翎，赵安成. 基于径流调控利用的水土保持多元综合治理模式研究[C]//中国水利学会第四届青年科技论坛论文集，2008：425－428
9 晏清洪，原翠萍，雷廷武，等. 降雨类型和水土保持对黄土区小流域水土流失的影响[J]. 农业机械学报，2014，45(2)：169－175.
YAN Qinghong, YUAN Cuiping, LEI Tingwu, et al. Effect of rainstorm patterns and soil erosion control practices on soil and water loss in small watershed on Loess Plateau[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(2): 169－175. (in Chinese)
10 PENG T, WANG S. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China[J]. CATENA, 2012, 90(1): 53－62.
11 AN J, ZHENG F L, HAN Y. Effects of rainstorm patterns on runoff and sediment yield processes[J]. Soil Science, 2014, 179(6): 293－303.
12 LI Z, Li P, HAN J, et al. Sediment flow behavior in agro-watersheds of the purple soil region in China under different storm types and spatial scales[J]. Soil and Tillage Research, 2009, 105(2): 285－291.
13 赵西宁，吴普特，冯浩，等. 降雨径流调控利用与流域保水减沙效应研究[J]. 自然灾害学报，2014，23(4)：46－53.
ZHAO Xining, WU Pute, FENG Hao, et al. Study on rainfall and runoff regulation and regional effects of runoff conservation and sediment reduction[J]. Journal of Natural Disasters, 2014, 23(4): 46－53. (in Chinese)
14 陈卫宾，刘生云，董增川. 基于径流调控的水土保持措施优化配置[J]. 人民黄河，2010，32(3)：81－82.
CHEN Weibin, LIU Shengyun, DONG Zengchuan. Optimized arrangement of soil and water conservation measures based on runoff regulation and control [J]. Yellow River, 2010, 32(3): 81－82. (in Chinese)
15 赵克荣，陈丽华，肖洋. 黄土区径流调控技术体系[J]. 中国水土保持科学，2008，6(4)：94－99.
ZHAO Kerong, CHEN Lihua, XIAO Yang. Measure system of runoff control in Loess Region[J]. Science of Soil and Water Conservation, 2008, 6(4): 94－99. (in Chinese)
16 吴淑芳，吴普特，宋维秀，等. 坡面调控措施下的水沙输出过程及减流减沙效应研究[J]. 水利学报，2010，41(7)：870－875.
WU Shufang, WU Pute, SONG Weixiu, et al. Study on the outflow processes of slope regulated by works and its effects on overland flow and sediment reduction[J]. Journal of Hydraulic Engineering, 2010, 41(7): 870－875. (in Chinese)
17 吴淑芳，吴普特，原立峰. 坡面径流调控薄层水流水力学特性试验[J]. 农业工程学报，2010，26(3)：14－19.
WU Shufang, WU Pute, YUAN Lifeng. Hydraulic characteristics of sheet flow with slope runoff regulation [J]. Transactions of the CSAE, 2010, 26(3): 14－19. (in Chinese)
18 张敏，张明武，何桂英，等. 黄河下游不同峰型非漫滩洪水冲刷效率分析[J]. 人民黄河，2016，38(1)：1－4.
ZHANG Min, ZHANG Mingwu, HE Guiying, et al. Analysis of erosion efficiency in different flood wave type on non-floodplain flood in lower Yellow River[J]. Yellow River, 2016, 38(1): 1－4. (in Chinese)
19 李占斌. 黄土地区小流域次暴雨侵蚀产沙研究[J]. 西安理工大学学报，1996，12(3)：177－183.
LI Zhanbin. Study on small watershed single storm erosion sediment yield in loess region[J]. Journal of Xi'an University of Technology, 1996, 12(3): 177－183. (in Chinese)
20 李占斌，符素华，解建仓，等. 窟野河流域暴雨侵蚀产沙研究[J]. 水利学报，1998，29(增刊1)：19－24.
LI Zhanbin, FU Suhua, XIE Jiancang, et al. A study on storm runoff sediment yield in Kuyehe river watershed [J]. Journal of Hydraulic Engineering, 1998, 29(Supp. 1): 19－24. (in Chinese)
21 周佩华. 黄土侵蚀机理探讨[J]. 水土保持研究，1997，4(5)：40－46.

ZHOU Peihua. Discussion on mechanism of loess erosion[J]. Research of Soil and Water Conservation, 1997, 4(5): 40 – 46. (in Chinese)

22 王思远,王光谦,陈志祥. 黄河流域土地利用与土壤侵蚀的耦合关系[J]. 自然灾害学报,2005,14(1):32 – 37.
WANG Siyuan, WANG Guangqian, CHEN Zhixiang. Relationship between land use and soil erosion in Yellow River Basin[J]. Journal of Natural Disasters, 2005, 14(1): 32 – 37. (in Chinese)

23 高照良,付艳玲,张建军,等. 近50年黄河中游流域水沙过程及对退耕的响应[J]. 农业工程学报,2013,29(6):99 – 105.
GAO Zhaoliang, FU Yanling, ZHANG Jianjun, et al. Responses of streamflow and sediment load to vegetation restoration in catchments on the Loess Plateau[J]. Transactions of the CSAE, 2013, 29(6): 99 – 105. (in Chinese)

24 方海燕,蔡强国,陈浩,等. 黄土丘陵沟壑区岔巴沟下游泥沙传输时间尺度动态研究[J]. 地理科学进展,2007,26(5):77 – 87.
FANG Haiyan, CAI Qiangguo, CHEN Hao, et al. Research on the dynamics of temporal sediment transport in a gullied loess basin: the lower Chabagou creek on the Loess Plateau[J]. Progress in Geography, 2007, 26(5): 77 – 87. (in Chinese)

25 廖义善,卓慕宁,李定强,等. 基于GIS黄土丘陵沟壑区分布式侵蚀产沙模型的构建——以蛇家沟小流域为例[J]. 泥沙研究,2012(1):7 – 13.
LIAO Yishan, ZHUO Muning, LI Dingqiang, et al. A GIS-based distributed soil erosion and sediment yield model for typical watersheds in hilly loess areas: a case study in Shejiagou catchment [J]. Journal of Sediment Research, 2012(1): 7 – 13. (in Chinese)

26 蔡强国,刘纪根,刘前进. 岔巴沟流域次暴雨产沙统计模型[J]. 地理研究,2004,23(4):433 – 439.
CAI Qiangguo, LIU Jigen, LIU Qianjin. Research of sediment yield statistical model for single rainstorm in Chabagou drainage basin [J]. Geographical Research, 2004, 23(4): 433 – 439. (in Chinese)

27 崔灵周,李占斌,郭彦彪,等. 基于分形信息维数的流域地貌形态与侵蚀产沙关系[J]. 土壤学报,2007,44(2):197 – 203.
CUI Lingzhou, LI Zhanbin, GUO Yanbiao, et al. Fractal-information-dimension-based relationship between sediment yield and topographic feature of eatershed[J]. Acta Pedologica Sinica, 2007, 44(2): 197 – 203. (in Chinese)

28 廖义善,蔡强国,卓慕宁,等. 不同时空尺度下沟壑对流域侵蚀产沙的影响——以黄土丘陵沟壑区岔巴沟流域为例[J]. 地理科学进展,2009,28(1):47 – 54.
LIAO Yishan, CAI Qiangguo, ZHUO Muning, et al. Influence of channel networks on the sediment yield under variant temporal and spatial scales: a case study of Chabagou watershed[J]. Progress in Geography, 2009, 28(1): 47 – 54. (in Chinese)

29 杨涛,张鹰,陈界仁,等. 基于数字平台的黄河多沙粗沙区分布式水文模型研究——以黄河岔巴沟流域为例[J]. 水利学报,2005,35(4):456 – 460.
YANG Tao, ZHANG Ying, CHEN Jieren, et al. Study on distributed hydrologic model in Chabagou basin of Yellow River based on digital platform[J]. Journal of Hydraulic Engineering, 2005,35(4): 456 – 460. (in Chinese)

30 陈晓安,蔡强国,郑明国,等. 岔巴沟流域次暴雨坡面土壤侵蚀经验模型[J]. 地理科学进展,2011,30(3):325 – 329.
CHEN Xiao'an, CAI Qiangguo, ZHENG Mingguo, et al. Empirical soil erosion model for single rainstorm in Chabagou drainage basin[J]. Progress in Geography, 2011, 30(3): 325 – 329. (in Chinese)

31 方海燕,蔡强国,李秋艳. 黄土丘陵沟壑区坡面产流能力及影响因素研究[J]. 地理研究, 2009, 28(3): 583 – 591.
FANG Haiyan, CAI Qiangguo, LI Qiuyan. Study on the runoff generation capacity of slope surface and its influencing factors in a hilly loess region on the Loess Plateau[J]. Geographical Research, 2009, 28(3): 583 – 591. (in Chinese)

32 ZHENG M, LI R, HE J. Sediment concentrations in run-off varying with spatial scale in an agricultural subwatershed of the Chinese Loess Plateau[J]. Hydrological Processes, 2015, 29(26): 5414 – 5423.

33 XU J. Erosion caused by hyperconcentrated flow on the Loess Plateau of China[J]. CATENA, 1999, 36(1 – 2): 1 – 19.

(上接第 59 页)

100 FULLER I C, MARDEN M. Slope-channel coupling in steepland terrain: a field-based conceptual model from the Tarndale gully and fan, Waipaoa catchment, New Zealand[J]. Geomorphology, 2011, 128(3 – 4): 105 – 115.

101 BRASINGTON J, LANGHAM J, RUMSBY B. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport[J]. Geomorphology, 2003, 53(3 – 4): 299 – 316.

102 PETER K D, DOLEIRE-OLTMANNS S, RIES J B, et al. Soil erosion in gully catchments affected by land-levelling measures in the Souss Basin, Morocco, analysed by rainfall simulation and UAV remote sensing data[J]. CATENA, 2014, 113: 24 – 40.

103 STOCKER C, ELTNER A, KARRASCH P. Measuring gullies by synergetic application of UAV and close range photogrammetry: a case study from Andalusia, Spain[J]. CATENA, 2015, 132: 1 – 11.

104 ELTNER A, BAUMGART P, MAAS H, et al. Multi-temporal UAV data for automatic measurement of rill and interrill erosion on loess soil[J]. Earth Surface Processes and Landforms, 2015, 40(6): 741 – 755.

105 NEUGIRG F, KAISER A, SCHMIDT J, et al. Quantification, analysis and modelling of soil erosion on steep slopes using LiDAR and UAV photographs[J]. Proceedings of the International Association of Hydrological Sciences, 2015, 367: 51 – 58.