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Influence of intra-event-based flood regime on sediment flow behavior from a typical agro-catchment of the Chinese Loess Plateau

Le-Tao Zhang [a,b], Zhan-Bin Li [a,b,c,*], He Wang [d], Jun-Bo Xiao [d]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China
[c] State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an, Shaanxi 710048, PR China
[d] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China

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SUMMARY

The pluvial erosion process is significantly affected by tempo-spatial patterns of flood flows. However, despite their importance, only a few studies have investigated the sediment flow behavior that is driven by different flood regimes. The study aims to investigate the effect of intra-event-based flood regimes on the dynamics of sediment exports at Tuanshangou catchment, a typical agricultural catchment (unmanaged) in the hilly loess region on the Chinese Loess Plateau. Measurements of 193 flood events and 158 sediment-producing events were collected from Tuanshangou station between 1961 and 1969. The combined methods of hierarchical clustering approach, discriminant analysis and One-Way ANOVA were used to classify the flood events in terms of their event-based flood characteristics, including flood duration, peak discharge, and event flood runoff depth. The 193 flood events were classified into five regimes, and the mean statistical features of each regime significantly differed. Regime A includes flood events with the shortest duration (76 min), minimum flood crest (0.045 m s^{-1}), least runoff depth (0.2 mm), and highest frequency. Regime B includes flood events with a medium duration (274 min), medium flood crest (0.206 m s^{-1}), and minor runoff depth (0.7 mm). Regime C includes flood events with the longest duration (822 min), medium flood crest (0.236 m s^{-1}), and medium runoff depth (1.7 mm). Regime D includes flood events with a medium duration (239 min), large flood crest (4.21 m s^{-1}), and large runoff depth (10 mm). Regime E includes flood events with a medium duration (304 min), maximum flood crest (8.62 m s^{-1}), and largest runoff depth (25.9 mm). The sediment yield by different flood regimes is ranked as follows: Regime E > Regime D > Regime B > Regime C > Regime A. In terms of event-based average and maximum suspended sediment concentration, these regimes are ordered as follows: Regime E > Regime D > Regime C > Regime B > Regime A. Regimes D and E produce the most runoff volume and the largest amount of sediments, which indicates that these regimes must be at the focus of runoff regulation to control the sediments. Given that the event flood runoff depth remains constant, the sediment yield by different flood regimes is regulated to varying degrees by altering the event-based runoff–sediment relationship. Compared with Regime A, the average decrease rates in the area-specific sediment yield for Regimes B, C, and D are 33%, 78%, and 62%, respectively. The regulative effect of the flood regime conversion on sediment export can be described with several variables that indicate the depth-specific characteristics of individual flood events. Flood regimes indicate the runoff erosivity dynamics and the runoff energy dissipation rates in eroding soil and delivering sediments. Therefore, the flood-regime-dependent sediment flow behavior differs across all regimes. Overall, the predominated controlling factors that influence the final sediment export are regime based. Empirical regime-based runoff–sediment relationships were established via multiple stepwise regressions. The suspended sediment concentration that is driven by different flood regimes can be described by the power function or logarithmic–linear function of runoff-related variables, including instantaneous discharge, runoff erosive power, and event-based flow variability. The regressive equations can explain the major driving forces behind the suspended

* Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, PR China.
E-mail address: zbli@ms.iswc.ac.cn (Z.-B. Li).

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sediment concentration dynamics. This study highlights the potentials of runoff self-regulation in controlling soil erosion and sediment delivery. The results may provide some evidence for flood regime classification, improve the overall evaluation of the sediment reduction benefits of the runoff regulation system, enrich runoff regulation theory, and improve the runoff control at the catchment scale.

1. Introduction

Soil erosion, which is associated with subsequent sediment delivery, is a complex scale-dependent geomorphological phenomenon that is influenced by the tempo-spatial variability of hydrologic processes (Cammeraat, 2004; López-Tarazón et al., 2010; Mayor et al., 2011; R Mkens et al., 2002). Therefore, a precise understanding of the runoff and erosion responses under various hydrological regimes may facilitate a profound recognition of the essential driving forces behind the erosion variations between situations and sediment dynamics across sites. Over the past few decades, the evolution of rainfall regimes across sites and the influence of rainfall spatial-temporal variability on watershed hydrologic responses have been extensively investigated to improve the accuracy of hydrological modeling at catchment outlets (Emmanuel et al., 2015; Ouarda et al., 2014; Paschalis et al., 2014; Shen et al., 2012; Strauch et al., 2015; Suhaila et al., 2011; Zhao et al., 2013; Zoccatelli et al., 2010). However, numerous studies have merely focused on the watershed hydrological responses to rainfall tempo-spatial heterogeneity and soil conservation measures (Dou et al., 2009; Faurès et al., 1995; Gao et al., 2015; Morin et al., 2006; Mu et al., 2007; Wei et al., 2009), whereas only a few studies have investigated the effects of hydrologic regimes on soil erosion processes and sediment behavior (Zhang et al., 2016). Consequently, the link between soil erosion responses and various hydrologic regimes has not yet been thoroughly examined because of limited studies and data.

Rainfall regimes, or the time- and spatial-varied characteristics of rainfall events, have received considerable attention in studying the rainfall-induced runoff and erosion processes at the slope and catchment scale (Ahmed et al., 2012; An et al., 2014; Dunkerley, 2012; Fang et al., 2008a; Frauenfeld and Truman, 2004; Hancock, 2009; Ran et al., 2012; Torri et al., 1999). The accurate identification of runoff–sediment relationships that underlie different rainfall patterns can help improve the reliability of soil erosion predictions, promote a practical-based design, and implement anti-erosion techniques (Fang et al., 2008a, 2012; Flanagan et al., 1988; Li et al., 2009; Parsons and Stone, 2006; Peng and Wang, 2012; Ran et al., 2012; Wei et al., 2007; Yan et al., 2014). As a basic erosive agent and medium for sediment delivery, the surface runoff of spatial–temporal variability directly determines the potential of water flows to erode soil and transport sediment (Zhang et al., 2015). Currently, the regulation effects on sediment dynamics by time-varied runoff heterogeneity are not fully clarified in terms of the function of soil-erosion-alleviating systems, thereby limiting the present understanding of the functions of anti-erosion strategies and the benefits of soil erosion control techniques. An improved recognition of the functions of anti-erosion strategies in regulating the tempo-spatial patterns and processes of surface runoff, coupled with the consequential erosion effects, will facilitate a reasonable set-up and optimized disposition of soil erosion control measures in cultivated watersheds. In this case, the soil erosion rates and sediment behavior that are controlled by different spatial–temporal patterns of surface runoff must be accurately quantified and effectively described. Therefore, further guidance must be provided for alleviating soil loss on the basis of runoff regulation and control, particularly in the regions of the Chinese Loess Plateau (Guo and Duan, 2001; Zhao et al., 2015). Further rational-based benefit evaluation toward a comprehensive efficiency assessment of soil erosion control strategies must also be performed under different surface runoff spatial–temporal patterns and land use scenarios at various scales.

The Chinese Loess Plateau, which has long been suffering from severe soil erosion, is characterized by arid and semi-arid landscapes with deep groundwater. As a result, the intra-annual runoff distribution in the watershed cannot be effectively regulated even if the annual stream flow is reduced by integrated soil erosion control measures (Gao et al., 2013; Mu et al., 2007; Zhao et al., 2013). The soil erosion of the Loess Plateau is primarily induced by concentrated flows from strong rainfalls within a short duration, whereas the soil losses that are caused by one severe heavy storm can account for 60–90% of the annual soil losses in the region (Li et al., 2012; Zhou, 1997; Zhou and Wang, 1992). Given the specificity of soil erosion in this region, the present study highlights the tempo-spatial scale effects on sediment behavior by regulating an intra-event-based flood hydrograph. Consequently, further research must be performed immediately to discriminate and clarify the dynamic responses of soil erosion and sediment yielding processes under different intra-event-based flood regimes. The loess hilly gully region with a unique erosion environment produces pluvial erosion events that are driven by rainstorm floods. These events can provide abundant information on runoff and sediment for further studies on geomorphologic processes and hydrologic modeling. Analyzing these runoff–sediment events under different hydrologic regimes will help elucidate the function of runoff regulation and control in soil conservation. The Chabagou watershed has always been a desirable experimental site for conducting related studies on the runoff–sediment relationship, its change, and its catchment hydrologic modeling in the loess hilly gully region (Chen, 2001; Fang et al., 2008b; Guo et al., 2014; Zheng et al., 2013, 2012). The nested hydrometrical stations as well as the sloping runoff fields of different spatial scales within the watershed provide sufficiently long time-sequenced hydrological observations and sediment measurements for relevant analyses and simulations. Therefore, a typical cultivated Tuanshangou catchment without management was selected in this study to examine the effects of intra-event-based flood regimes on sediment flow behavior under a near-natural condition with minimal human disturbance. Specifically, this study aims (1) to determine basic runoff-related indicators to summarize the properties of the intra-event based flood regimes and classify different flood regimes, (2) to quantify the basic characteristics of flood runoff and sediment yields under different flood regimes, (3) to examine the flood-regime-driven regulating effects on sediment yield from individual flood events, considering that the event flood runoff depth remains constant, and (4) to describe the flood-regime-driven sediment behavior with effective runoff-related indicators. This study is expected to produce positive findings to enrich runoff regulation and control theory as well as to improve the soil erosion control level at the catchment scale.

The paper is organized as follows. Section 2 describes the study region as well as provides the documentation of the flood events, the analytical methodology for generalizing intra-event-based flood regimes, and the basic equations for the data collection.