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Impacts of rainfall and inflow on rill formation and erosion processes on steep hillslopes

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ABSTRACT

Limited information has isolated the impacts of rainfall on rill formation and erosion on steep hillslopes where upslope inflow simultaneously exists. Field simulation experiments were conducted on steep hillslopes (26°) under rainfall (60 mm h^{-1}), inflow (6, 12, 18, 24, 30, 36 L min^{-1} m^{-1}), and combination of rainfall and inflow to explore the impacts of rainfall on rill formation, and the interaction between rainfall and inflow on soil erosion. Rainfall decreased soil infiltration rate (10%–26%) mainly due to soil crust by raindrop impact. Rainfall strengthened rill formation, which behaved in the increment in rill width (5%–26%), length (4%–22%), and depth (3%–22%), but this increment decreased as inflow rates increased. Additionally, the contribution of rainfall on rill formation was most significant at the initial stage, followed by the final stage and active period of rill development. Rainfall increased rill erosion (8%–80%) and interrill erosion (36%–64%), but it played a dominant role in increasing interrill erosion under relatively high inflow rates. The most sensitive hydrodynamic parameter to soil erosion was shear stress and stream power under inflow and 'inflow + rainfall' conditions, respectively. For the lowest inflow rate, the reduction in soil loss by interaction between rainfall and inflow accounted for 20% of total soil loss, indicating a negative interaction. However, such interaction became positive with increasing inflow rates. The contribution rate to rill erosion by the interaction was greater than that of interrill erosion under relatively low inflow rates. Our results provide a better understanding of hillslope soil erosion mechanism.

1. Introduction

Soil erosion can be caused by overland flow, by rainsplash, and by the combination of overland flow and rainfall impact (Hairsine and Rose, 1991; Salles et al., 2000; Beuselinck et al., 2002). The interrill erosion process mainly results from the detachment of soil particles by raindrop impact and transport of the detached particles by overland flow (Kinnell, 2005). The rill erosion process primarily results from soil detachment and transport by concentrated flow (Kimaro et al., 2008). The transport rates of soil particles by rain splash often are negligible (Kinnell, 1991), whereas raindrop impact enhances sediment delivery by breaking down aggregates into finer particles and increasing runoff turbulence (Foster, 1982; Dunne et al., 1991). In this way, raindrop impact can strongly influence the interrill and rill erosion processes by modifying soil surface properties and flow hydraulics (Bryan, 2000; Wirtz et al., 2012). Raindrop detachment with transport by rain-impacted flow plays an important role in moving soil materials from interrill areas to rills (Young and Wiersma, 1973; Kinnell, 1988). However, both detachment and transportation of soil particles by raindrop impact are closely related to the ratio of flow depth and raindrop diameter (Singer et al., 1981; Gabet and Dunne, 2003; Gao et al., 2003). Many pioneer researchers found that raindrops impacting on shallow overland flows increases soil loss (Ellison, 1945; Ekern, 1950; Walker et al., 1978; Guy et al., 1987), which was classified as rainfall-driven erosion processes by Kinnell (2005). Although numerous studies have found that soil loss due to flow-driven erosion processes can be increased by rainfall impact (Jomaa et al., 2010; Kinnell, 1993, 2005; Quansah, 1985), most of the researches focused on the impact of rainfall on interrill erosion on relatively gentle slopes. Limited information has isolated the quantitative contribution of rainfall on interrill erosion and rill erosion separately on steep hillslopes where upslope inflow simultaneously exists.

The detachment and transport processes of soil particles in rills and interrill areas on hillslopes are simultaneously influenced by raindrop impact, overland flow, and their interaction (Liu and Singh, 2004). Rouhipour (1997) found that interaction between rainfall-driven and flow-driven erosion processes cannot be

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Symbols and abbreviations

S	slope steepness, °
q	inflow rate per unit width of the plot, L min^{-1} m^{-1}
f_i	soil infiltration rates, %
h	mean flow depth, m
V_S	the measured surface flow velocity, m s^{-1}
α	correction factor in determining mean velocity
V	mean flow velocity, m s^{-1}
V_A	surface flow velocity for the entire slope, m s^{-1}
V_R	surface flow velocity for the rills, m s^{-1}
V_I	surface flow velocity for the interrill areas, m s^{-1}
V_C	mean surface flow velocity for each slope segment, m s^{-1}
g	acceleration due to gravity, m s^{-2}
Re	Reynolds number
Fr	Froude number
f	Darcy-Weisbach resistance coefficient
C_V	coefficients of variations
SL	soil loss, kg
S_A, S_B, S_C	soil loss rate in type A, B, and C experiments, g m^{-2} min^{-1}
S_R	soil loss rate derived from rainfall impact, g m^{-2} min^{-1}
S_I	soil loss rate derived from interaction between rainfall and inflow, g m^{-2} min^{-1}
τ	shear stress, N m^{-2}
W	stream power, N m^{-1} s^{-1}
φ	unit stream power, m s^{-1}

neglected. However, current physically based soil erosion models, such as WEPP (Nearing et al., 1989; Foster et al., 1995) does not directly consider the interaction between rainfall-driven and flow-driven erosion processes. The WEPP model assumes that rainfall erosion occurs only in interrill areas and flow erosion occurs in rills. Asadi et al. (2007) found the interaction between interrill erosion processes was generally positive for three different soils. Rouhipour et al. (2006) observed negative interaction for a loamy sand, and positive interaction for a silty loam on extremely gentle slopes (<1°) where rills were absence under laboratory conditions. Laboratory experiments conducted on gentle slopes (10°) with the Mollisol from Northeast China by Wen et al. (2015) showed that interaction between rainfall and inflow significantly increased hillslope soil erosion, indicating a strongly positive interaction. Rouhipour et al. (2006) found that interaction between erosion processes driven by rainfall and by flow changes with flow stream power. Though great efforts have been made to investigate the effect of interaction between erosion processes driven by rainfall and flow, however, most of which focused on gentle slopes where rills were rarely under laboratory conditions (Asadi et al., 2007). Information concerning the interaction between soil erosion processes on steep hillslopes where rills are significant are not available.

When the energy of rainfall or overland flow is sufficient, soil erosion on steep hillslopes can quickly evolve from splash or sheet erosion to rill erosion (Stefano et al., 2013). The evolution from interrill to rill erosion can greatly affect runoff, soil loss and micromorphology as well as the dynamics of the slope surface (Fang et al., 2015). The confluence of surface flow in the interrill erosion areas prepared hydrodynamic conditions for rill development (Bruno et al., 2008). The partitioning of runoff into rills and interrill areas is generally static in current soil erosion models, although the balance between these erosion processes is dynamic and complex because the microtopography is changing over time (Berger et al., 2010). Rill morphology plays a significant role in determining surface runoff and soil loss from hillslopes (Shen et al., 2015). The detailed descriptions of rills include rill length, width, and depth, as well as the evolution process of the rill networks (Raff et al., 2004). The development of rill networks contributes to an increase in runoff connectivity and concentration of flow along the channeling network (Heras et al., 2011). It is a general agreement that concentrated flow causes rill development (Romero et al., 2007), while raindrop impact plays more significant roles in interrill erosion (Wirtz et al., 2012). However, the role of raindrop impact plays in the process of rill formation and development on steep hillslopes where upslope inflow simultaneously exists has not been researched in detail.

The impact of raindrops on the shallow flowing water contributes to flow turbulence, thus changing the flow characteristics (Gabet and Dunne, 2003; Gao et al., 2005). Meanwhile, raindrop impact enhances soil detachment and transport, which may alter flow hydraulics and dynamic mechanism of soil erosion (An et al., 2012). However, previous studies mainly focused on the effects of rainfall impact on flow hydraulics on relatively gentle slopes under laboratory conditions (Moss, 1988; An et al., 2012). The different erosion dynamic mechanism of overland flow with and without rainfall impact on steep hillslopes need to be further researched (Lu et al., 2016). Flow velocity is directly related to soil loss, sediment transport, deposition, rill formation and development (Li et al., 2016; Pan et al., 2015). The difference of flow velocity between rills and interrill areas not only reflect surface roughness, flow depth relationships, but also raindrop impact. Shear stress, stream power, and unit stream power are commonly used hydrodynamic parameters to calculate soil detachment rates and reflect the critical hydrodynamic condition of soil erosion occurrence (Foster et al., 1984; Nearing et al., 1991; Abrahams et al., 1996).

For the issues mentioned above, most previous studies were investigated on relatively gentle slopes under laboratory conditions (An et al., 2012). However, there are differences of soil erosion processes and runoff hydraulics between gentle slopes and steep slopes. In addition, it is very difficult to avoid the disturbance of the natural soil structure in laboratory experiments. Therefore, a series of field simulation experiments were conducted on field steep hillslopes (26°) to address these issues. The objectives of this study are (1) to investigate the impacts of rainfall on rill formation and soil erosion processes; (2) to evaluate the effect of interaction between rainfall and inflow on soil erosion. The findings will improve understanding of erosion mechanism on steep hillslopes.

2. Materials and methods

2.1. Study area and experimental facilities

The field experiments were conducted at the Huailai Field Experimental Station of the State Key Laboratory of Earth Surface Processes and Resource Ecology, which is affiliated with Beijing Normal University. The Station (40°15′32″ N, 115°37′ 01″ E) is located in the loess hilly region at Huailai Basin of Hebei Province, North China. This region belongs to a transition zone between the northwest plateau of Beijing and the North China Plain, which is one of the key areas implementing soil and water conservation in China (Tian et al., 2015). The main reasons for the soil erosion