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A simulation of rill bed incision processes in upland concentrated flows

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ABSTRACT

Quantifying rill bed incision provides fundamental information for process-based erosion modeling; while the morphodynamic and hydrodynamic mechanism in bed incision processes are still unclear. Thus, experiments were conducted to examine rill bed incision processes in upland concentrated flows. DEMs (2 mm × 2 mm resolution) obtained by photogrammetry were used for rill bed morphology analysis. Rill channel (2.0 m-long, 0.08 m-wide and 0.15 m-deep) with two slope gradients (15° and 20°) were subjected to four overland flow rates (1.0, 2.0, 3.0 and 4.0 L min^{-1}). The results showed that sediment delivery, rill bed incision rate and average rill depth increased with inflow rate and bed slope. Sediment delivery increased from 0.060 to 0.226 kg min^{-1} per 1 L min^{-1} inflow increment and from 0.043 to 0.207 kg min^{-1} when bed slope increased from 15° to 20°. In a well-developed rill channel, rill bed incision could be divided into three phases: pre-headcut formation (dominated by rill flow shear stress), headcut incision (dominated by headcut advancing) and post-headcut incision (dominated by rill flow shear stress). Headcut incision phase, which only accounted for < 15% of total experimental time, produced > 65% of rill bed sediment. In the pre-headcut formation phase, rill flow velocity, shear stress and stream power increased with increases of inflow rate and slope gradient. Conversely, flow velocity showed no evident trend with increased inflow rate and bed slope during headcut incision phase. Initial headcut advancing rate could be predicted by a non-linear function based upon soil characteristics, rill flow shear stress and headcut height. Sediment delivery showed a power function with the product of inflow rate and squared bed slope. Because rill bed incision is dominated by headcut advancement and incision, practices for controlling headcut initiation should be implemented to decrease hillslope soil loss.

1. Introduction

Rill erosion accounts for > 70% of total sediment yield on rill and inter-rill dominated areas (Shen et al., 2016; Xiao et al., 2017a). Sediment yield increases significantly after rill formation due to the increased concentrated flow depth, velocity and shear stress compared to inter-rill flow (Lal, 2002; Liu et al., 2011). Rill development is a complex physical process which includes one or more following sub-processes: headcut migration, bed incision and sidewall expansion (Meyer et al., 1975; Bingner et al., 2016). The dominant sub-process is different at different rill development stages (Shen et al., 2016). However, rill bed incision, depending upon landscape slopes and soil conditions, may play a more important role than sidewall expansion after headcut retreat (Bingner et al., 2016). Understanding the processes and mechanisms of bed scour and headcut migration can help improve the Water Erosion Prediction Project (WEPP) (Nearing et al., 1990; Zhu et al., 1995). Characterizing rill erosion processes and estimating their contributions, especially rill bed incision, on the Loess Plateau of China are important for understanding loessial rill erosion processes in this region (Shen et al., 2016).

Based on the assumption that rill cross-sectional area is constant (i.e. rill width/depth changes less than rill length), rill volume prediction equations have been fitted to rill length (Capra et al., 2009; Di Stefano and Ferro, 2011; Woodward, 1999). Liu et al. (2015) indicated that an approach including maximum rill depth and length was more accurate in predicting rill erosion than those solely based on rill length. Woodward (1999) pointed out that accurately estimating rill depth was a key factor to improving rill erosion model prediction accuracy. As a result, research on rill depth dynamics and its hydrodynamic mechanisms are of great importance to rill erosion modeling.

Currently, studies on rill bed incision have mainly focused on contributions of rill bed incision to soil loss (Shen et al., 2016), rill incision

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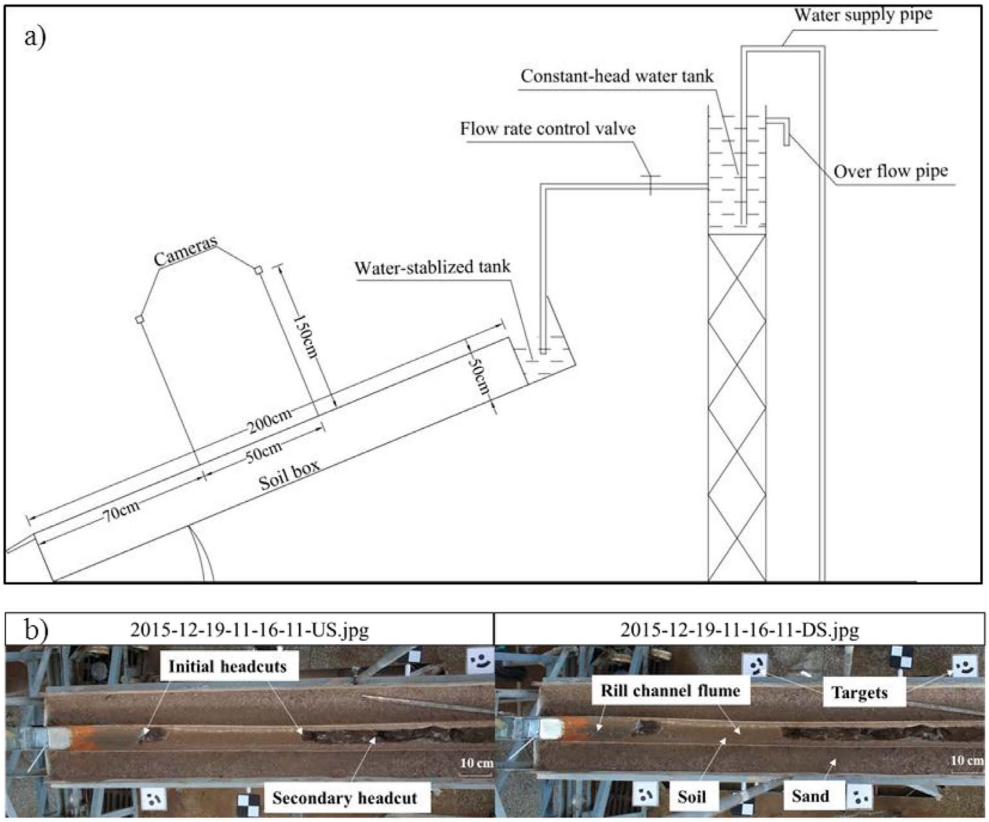

Fig. 1. a) Sketch of the experimental facilities and b) example of paired photos obtained from photogrammetry during experiment. 2015-12-19-11-16-11 represents year-month-date-hour-minute-second of the time the photo was taken. US and DS represent upstream and downstream, respectively.

circularity (Bryan and Poesen, 1989; Bennett et al., 2000), affecting factors (e.g. soil erodibility, bed slope, upslope inflow rate, sediment concentration and near-surface hydraulic gradient) (Bryan and Poesen, 1989; Slattery and Bryan, 1992; Bennett et al., 2000; Alonso et al., 2002; Liu et al., 2015) and rill incision numerical modeling (Zhu et al., 1995; Favis-Mortlock, 1998; Casal et al., 2003; Jia et al., 2005). Evans and Boardman (2003) indicated that sufficient runoff volume and velocity were prerequisites for producing incisive flow that may lead to bed incision. Rill incision starts when concentrated flow tractive forces exceed rill bed soil entrainment resistance.

Rill depth does not increase uniformly with slope length as relatively narrow and deep rills (erosion zone) can alternate with straight and shallow rills (deposition zone), which may be attributed to the significant difference in erodibility between top soil (surface seal) and subsoil (Bryan and Poesen, 1989). Soil surface seal protects the rill bed from being eroded, which leads to low soil detachment rate of the rill bed by concentrated rill flow (Römkens et al., 1990). Failure of surface seals facilitates the formation of headcuts, bed incision and rill development (Römkens et al., 1990; Bennett et al., 2000). Headcuts are step changes in elevation that occur in channel networks (Gardner, 1983; Mosley, 1974). Based on the occurrence, position and time, Bryan and Poesen (1989) and Slattery and Bryan (1992) classified these headcuts into initial headcut and secondary headcut. However, it is hard to accurately measure rill depth variation and hydrodynamic characteristics near headcuts due to the rapid development of rills, narrow and deep rill morphologies and high sediment concentrations within rill flow (Römkens et al., 1990; Slattery and Bryan, 1992). Rill incision mechanism research, before and after surface seal failure, still needs to be intensified. It limits the establishment of soil erosion models for rill bed incision.

Rill morphology research based upon traditional surveying (rill survey with steel ruler, profilometer, etc.), high precision GPS (RTK) and TLS (terrestrial laser scanning) have deepened the understanding of the magnitude of hillslope erosion (Rejman and Brodowski, 2005; Vinci et al., 2015; Shen et al., 2016; Vinci et al., 2016; Qin et al., 2017). However, manual measurements have some drawback including low outcome precision, low work efficiency, overestimates of rill depths and underestimates of rill widths et al. (Qin et al., 2016; Vinci et al., 2016). RTK and TLS greatly improved work efficiency and measuring accuracy in some extent while still have limitations caused by the quick changes of soil surface morphology (Momm et al., 2015). Photogrammetry, based on the theory of remote-sensing imagery interpretation, provides a low-cost and labor-saving way to acquire a large number of points without disturbing the soil surface, with acceptable precision by using ordinary cameras or smartphones (Tarolli, 2014; Eltner et al., 2016; Wells et al., 2016; Qin et al., 2018; Vinci et al., 2017). The capability of photogrammetry (including Structure from motion photogrammetry and UAV) to produce high precision DEMs/DTMs that may be used to characterize erosion-deposition mechanics to provide new insight on monitoring rill morphology on movable soil beds (Berger et al., 2010; Gessesse et al., 2010; Tarolli, 2014; Bingner et al., 2016; Wells et al., 2016).

Concentrated-flow erosion is a major component of cropland erosion, and experiments that focus on specific processes are needed (Zhu et al., 1995). In this study, rill channel flumes were formed to investigate the effects of slope gradient and inflow rate on rill bed incision based on high precision DEMs obtained from photogrammetry. The specific objectives of this study were: 1) to detect rill depth variation with time and slope length under different experimental designs, 2) to discuss rill flow hydrodynamic characteristics during different rill bed incision phases, and 3) to establish predictive equations for headcut advancing rate and sediment delivery rate caused by bed incision.