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Flume experimental evaluation of the effect of rill flow path tortuosity on rill roughness based on the Manning–Strickler equation

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ABSTRACT

Numerous soil erosion models compute concentrated flow hydraulics based on the Manning–Strickler equation ($v = k_{St}\,R^{2/3}\,I^{1/2}$) even though the range of the application on rill flow is unclear. Unconfined rill morphologies generate local friction effects and consequently spatially variable rill roughness which is in conflict with the assumptions of (sectional) uniform channel flow and constant channel roughness of the Manning–Strickler equation.

The objective of this study is to evaluate the effect of rill morphology on roughness and hence to assess the Manning–Strickler roughness coefficient (k_{St}) by rill morphological data. A laboratory experiment was set up to analyse rill hydraulics and roughness of I.) Free Developed Rill (FDR) flows and II.) Straight Constrained Rill (SCR) flows in the flume. The flume experiment generated Manning–Strickler roughness coefficients (k_{St}) between 22 $m^{1/3}\,s^{-1}$ and 44 $m^{1/3}\,s^{-1}$ reflecting a potential area of the roughness parameter uncertainty. It was found that FDR experiments generated significantly lower k_{St} values compared to SCR experiments, because skin and local friction effects in the FDR experiments were more efficient reducing flow velocity probably due to higher energy dissipation. Rill flow path tortuosity (*Tort*) was used to describe the rill morphology of the experiments and correlation statistics between *Tort* and k_{St} identified considerable explanatory capacity of rill flow path tortuosity on rill roughness. The flume study demonstrated that a regression model between *Tort* and k_{St} can be used to assess local friction effects of unconfined rill morphologies and hence to reduce the area of uncertainty of the Manning–Strickler roughness parameter.

1. Introduction

Concentrated flow in numerous soil erosion models is computed based on uniform flow equations designed for river scale hydraulics (Govers et al., 2007) and therefore the application on rill flow is limited. Uniform flow equations represent turbulent and uniform open channel flow (Chow, 1959) and unconfined rill flow in nature deviates from this concept. Unconfined rill morphologies generate local friction effects and consequently spatially variable rill roughness which is conflict with the assumptions of the commonly used flow equation of Darcy–Weisbach, Manning or Chezy (Gilley et al., 1990).

However, practicable input data requirements enable straightforward modelling and therefore particularly the Manning–Strickler equation is often used in physical based erosion models (Govers et al., 2007) even though consequential gaps have been intensively discussed in the past (e.g., Gilley et al., 1990; Govers et al., 2007; Julien and Simons, 1985; Moore and Burch, 1986; Nearing et al., 1997). Channel friction is scale dependent as there is a changeover from skin friction to form drag due to pressure differences around individual obstacles in a channel (Judd and Peterson, 1969; Lee and Ferguson, 2002) and therefore the constant Manning–Strickler roughness coefficient is insufficient to describe variable friction effects. Non-uniform flows of step and pool morphologies can generate considerable supplementary friction loss due to transient flow conditions and hydraulic jumps which can dominate total flow resistance (Comiti and Lenzi, 2006; Comiti et al., 2007; Curran and Wohl, 2003; MacFarlane and Wohl, 2003). Turbulent and rough channel flow conditions, required by the Manning–Strickler equation (Julien and Simons, 1985) might be achieved in large scale rill flows, but the assumptions of approximate steady-state and uniform channel flow might fail for rill as well as river scale flows.

Moreover, Manning's equation lacks the ability to describe the flow of an actively eroding rill because of variable interactions between rill flow, soil erosion and sediment transport (Nearing et al., 1997). The sediment transport of a rill differs over time and space as an unsaturated rill flow needs to recover within a distance and based on this, sediment concentration controls the rill erosion rate (Liu et al., 2007; Wirtz et al., 2012) and consequently the rill morphological development. This

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conflicts with the often used model assumption that rill flow occurs on a surface with a fixed rill structure during the entire erosion process (Parsons et al., 1997). Various researchers suggested relations between sediment transport and flow hydraulics to be implemented in physical based soil erosion models to account for the effects of transient runoff processes (e.g. Aksoy and Kavvas, 2005; Lei et al., 1998; Nearing et al., 1997; Smith et al., 2011; Takken et al., 2005). For example Lei et al. (1998) presented a finite element model which self-generates the incision of a rill over space and time, even though lateral rill morphological impacts on the rill flow were neglected in this model.

However, Merritt et al. (2003) argued that most erosion models are inappropriate for predicting catchment scale and event-based sediment transport because of the lack of readily available watershed data and/or unsuitability of the model assumptions and therefore simplified flow equations are still in demand. Manning's equation is commonly accepted for overland flow as well as stream flow models and therefore it is preferable to use one equation for various model applications (Hessel et al., 2003). However, there is a gap between the complex rill flow in nature and idealized channel flow concepts commonly used to simulate such processes in watershed scale, even though the magnitude of the gap might vary. The objective of this study is to evaluate this gap and to explore interactions between rill morphology and rill roughness based on experimental data. A flume study was designed to develop unconstrained meandering rill erosion but also straight in line rill erosion morphologies to I.) explore a potential range of Manning–Strickler roughness due to different rill morphologies and II.) to evaluate the effect of rill flow path tortuosity on rill roughness.

2. Materials and methods

2.1. Experimental design

The experiment was carried out in a 1.95 m long, 0.60 m wide and 0.35 m deep flume with a 10% inclination (Fig. 1). At the inlet a water reservoir with a 0.35 m wide rectangular opening was installed to provide a steady state inflow over the crest of the reservoir. At the bottom of the flume a system of drainage outlets was installed to set the soil subsurface to free drainage condition. The interface between the soil and the drainage outlets was an 8 cm thick gravel layer that provided even infiltration across the soil bed. At 2 m above the soil surface, a system of stereo cameras was set up to monitor the channel development at 0.02 Hz. The stereo system covered an overlapping flume length of 128 cm which was the 'control section' of rill morphological analyses.

The soil used in this experiment was a loam with 32% sand, 49% silt and 19% clay based on a US particle size classification. The collected soil was air dried, ground and sieved to <2 cm and coarse stones, crop residues and roots were discarded from the material. The soil was packed in a 17 cm thick layer on the gravel sub-layer and its surface was shaped to the desired initial condition (Fig. 2) by pulling a metal panel along the flume. Once the soil bed was prepared a simulated rainfall at 15 mm h^{-1} intensity was applied with an oscillating nozzle rainfall simulator (Foster et al., 1979). As supported by several studies (e.g., Römkens et al., 1997; Wells et al., 2009), the purpose of the rainfall application was to consolidate the soil surface and to create a well-developed and reproducible surface seal. After 2 h of rainfall simulation and 1 h of resting time the soil was prepared for the experiment and average bulk density of the top soil layer was 1.41 g cm^{-3}.

Two different initial flume conditions were set up to generate: I.) Free Developed Rill (FDR) experiments of unconstrained rill erosion on a plain soil bed and II.) Straight Constrained Rill (SCR) experiments of concentrated flow erosion in a prepared straight initial rill. The FDR experiments represent the unconstrained rill conditions in the field whereas the SCR experiments represent idealized channel assumptions of uniform channel flow. For the FDR preparation (Fig. 2) the 60 cm wide flume was shaped by a trapezoidal panel to a plain and cross-sectional horizontal soil surface of 35 cm width. The side-banks of the flume boundaries were inclined to avoid flume border impacts on the meandering rill of FDR runs. At the outlet of the flume a 5 cm deep initial head-cut was prepared to induce retrograde channel erosion when the water overflows the rim. The scour-shaped head-cut at the outlet provided a single rill development in the flume which was essential to explicitly link runoff to individual rill morphology. For SCR preparation (Fig. 2) similar soil bed treatment was undertaken (compared to FDR preparation), but with a central initial channel to enforce the incipient discharge to develop straight aligned rill erosion. Each rill experiment (FDR and SCR) was executed with two different discharges ($Q_1 = 0.145$ l s^{-1} and $Q_2 = 0.270$ l s^{-1}) which led to four different set-up conditions. All set-ups were replicated three times. The experiment started when the adjusted discharge (Q_1 or Q_2) overflowed the outlet of the water reservoir and came into contact with the prepared soil surface. At initial stage of FDR experiments a shallow sheet flow developed on the plain soil bed and concentrated locally at the prepared head-cut at the outlet. Local runoff concentration induced retrograde moving head-cut erosion through the soil bed enabling free meandering rill erosion in the flume. In the SCR experiments incipient runoff was forced to concentrate in the straight initial channel, and the prepared head-cut at the outlet induced the deepening and widening of the straight initial channel until stable rill morphology established. Rill development was observed in both experiments until the moving head-cut reached the upper flume boarder and subsequent channel incision declined which was indicated by the distinctive decrease of the observed sediment concentration. All further results presented in this paper refer to equilibrium erosion stage of a quasi-stable rill morphology and steady state rate of sediment transport which

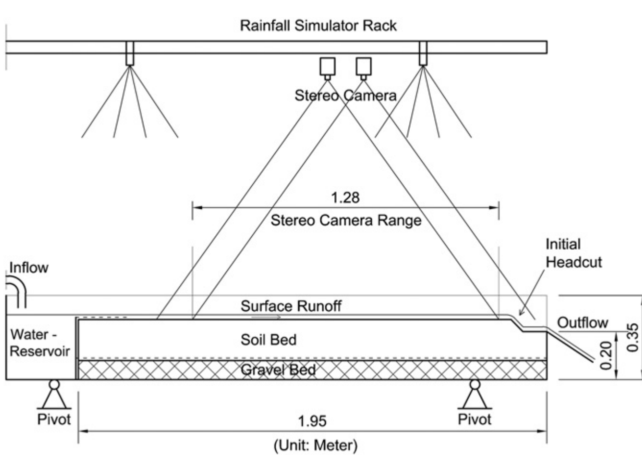

Fig. 1. Schematic of the flume construction.

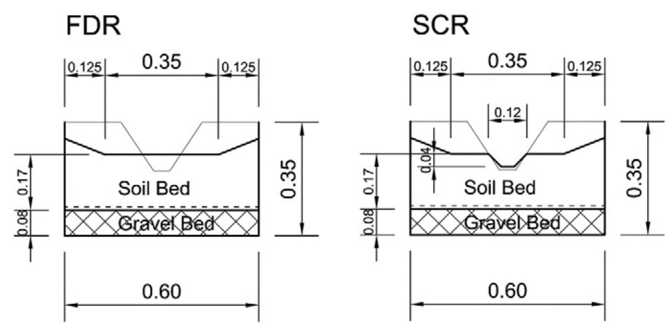

Fig. 2. Cross section schematics (unit: metre) of the flume and the initial soil bed preparation of Free Developed Rill (FDR) and Straight Constrained Rill (SCR) conditions.