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Field experiments for understanding and quantification of rill erosion processes

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ABSTRACT

Despite many efforts over the last decades to understand rill erosion processes, they remain unclear. This paper presents the results of rill experiments accomplished in Andalusia in September 2008 using a novel experimental set up. 72 L of water are introduced with an intensity of 9 L min^{-1} into a rill. Rill cross sections, slope values, flow velocities and sediment concentrations were measured and these values were used to calculate sediment detachment and transport. Each experiment was repeated once within 15 min. With this new experimental setup it is possible to calculate several hydraulic parameters like hydraulic radius, wetted perimeter, flow cross section, transport rate and transport capacity which are usually estimated from coarse flow and rill parameters. In rill experiments, four different natural rills were flooded with the same experimental setup. Several processes like transport of loose material, erosion, bank failure and knickpoint retreat and the runoff effectiveness showed different and variable intensities. The sediment concentrations ranged between 5.2 and 438 g L^{-1}. In most cases, detachment rates are close to the transport capacity and, in some cases, the transport capacity is even exceeded. This can be explained by the occurrence of different erosion processes within a rill (e.g. detachment, bank failure, and headcut retreat) which are not all explained by the given equations. The results suggest that the existing soil erosion equations based on shear forces exerted by the flowing water are not able to describe rill erosion processes satisfactory. Too many different processes with a high spatial and temporal variability are responsible for rill development.

1. Introduction

Soil erosion in general, and the development of rills in special, is the result of a very complex interaction of soil properties with a high spatial and temporal variability (Nachtergaele et al., 2001, 2002; Poesen et al., 1999) in which the morphology of a rill and the rill's headcut morphology (Flores-Cervantes et al., 2006) may be determinant as well as stochastically driven processes (Sidorchuk, 2005). This leads to great difficulties in quantifying soil erosion processes and makes soil erosion measurements hardly comparable (Knapen et al., 2007; Auerswald et al., 2009; Stroosnijder, 2005).

The two main processes in soil erosion are inter-rill and rill erosion by flowing water, however the mechanisms of these two processes are completely different. The detachment in inter-rill erosion is caused and enhanced by drop-impact (Beuselinck et al., 2002) and, in addition to the soil's intrinsic characteristics (Kuhn and Bryan, 2004; Kuhn et al., 2003; Le Bissonnais et al., 2005), is thought to depend mainly on rainfall intensity (Brodie and Rosewell, 2007; Bryan, 2000). Rill erosion is, in contrast, caused by the concentrated flow of water (Bryan, 2000; Govers et al., 2007; Knapen et al., 2007) and is considered to be the most important process of sediment production (and thus, soil loss) (Cerdan et al., 2002; Poesen, 1987). The resulting rills may be persistent and develop into gullies, hindering further land use (Woodward, 1999; Vandekerckhove et al., 1998). Especially on fallowland and shrubland, rills can develop without disturbance by land management measures like ploughing. In the Mediterranean, huge areas of fallowland and shrubland exist (Ries, 2003) thus rills can develop very fast and cause high soil losses.

Generally, rill erosion is understood as the effect of flowing water exceeding a certain threshold of soil resistance (Knapen et al., 2007). During the last decades, several approaches to describe and predict soil detachment and sediment transport in rills have been developed, and great effort has been made to evaluate their suitability for that purpose (Giménez and Govers, 2002; Govers et al., 2007; Hessel and Jetten, 2007). Unfortunately, the different approaches to describe this phenomenon have turned out to be at least weak, if not contradictory (Giménez and Govers, 2002; Govers et al., 2007; Merz and Bryan, 1993). This is attributed mainly to methodological differences in all monitoring and experimental set-ups to achieve the rills (Knapen et al., 2007; Merz and Bryan, 1993). It also appears that particle detachment and sediment transport may be controlled by different characteristics of the flowing water and, therefore, a comprehensive description may not be possible (Govers et al., 2007). However, soil erosion measurements are still lacking (Stroosnijder, 2005) and there is a recognized need to perform field experiments to ascertain the role of rills in soil erosion (Govers et al., 2007). As the observation of

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erosion in the field is subordinated to the stochastic character of the erosion events (Auerswald et al., 2009) and to a high dependency of the measurement technique (Casali et al., 2006), standardized and reproducible field experiments are needed, in which the relevant parameters of runoff and sediment transport can be measured and which, at the same time, can produce data to characterize the rill's behaviour in its environment.

Most experimental work about rill erosion that has been carried out, both in the laboratory (Brunton and Bryan, 2000; Bryan and Poesen, 1989; Gilley et al., 1990; Huang et al., 1996; Mancilla et al., 2005) as well as under field conditions (De Santisteban et al., 2005; Helming et al., 1999; Rejman and Brodowski, 2005) used soils with different textures and natural or simulated rainfall. The aim of the research groups was to observe rill network formation (Bruno et al., 2008; Mancilla et al., 2005), define the initial conditions for rilling (Bruno et al., 2008; Bryan et al., 1998; Govers and Poesen, 1988; Slattery and Bryan, 1992; Torri et al., 1987), study the development of rill head morphology (Bruno et al., 2008; Brunton and Bryan, 2000), estimate the main hydraulic variables like cross-section area, wetted perimeter, hydraulic radius, mean velocity and shear stress (Bruno et al., 2008; Foster et al., 1984; Gilley et al., 1990; Giménez et al., 2004; Govers, 1992b) or propose mathematical models for estimating soil loss due to rill erosion (Favis-Mortlock, 1998; Favis-Mortlock et al., 2000; Bruno et al., 2008; Foster, 1982; Nearing et al., 1989).

In most laboratory experiments the effort is made to find relationships between different factors. The influence of runoff on soil detachment is an often investigated question. Other parameters often tested are slope length, percolation, rill development, critical Froude number, critical shear stress different soil characteristics, slope, rainfall intensity, flow velocity or flow velocity distribution, bed morphology and flow area.

In such a way, Bryan and Poesen (1989) tested, in laboratory experiments, the relationship between slope length, percolation, runoff and rill development. The flume used had a maximum length of 24.5 m, consisting of ten segments of 2.45 m. At the end of the flume, runoff was measured. They showed that runoff is not a simple function of rainfall excess and slope length but a more complex process dominated by surface sealing, rill development and headcut incision. Rill initiation is controlled by established threshold hydraulic conditions, the further development of the rills and headcuts is complex and depending on different thresholds. Torri et al. (1987) related in laboratory experiments, with variable slope, runoff and rainfall intensity, the critical Froude number and the critical shear stress to some soil characteristics. Critical shear stress was found to be correlated to soil shear strength. But this result could not be confirmed in all further studies. In another laboratory study, Nearing et al. (1991) measured flow shear stresses ranged from 0.5 to 2 Pa, while tensile strengths ranged from 1 to 2 kPa, a difference in magnitude of 1000. Despite this conflict, detachment rates of nearly 300 $g\,m^{-2}\,s^{-1}$ were measured. He explained this result with turbulent burst events which are much greater than the average flow shear stresses.

Giménez et al. (2004) tested, in a laboratory flume experiment, the velocity distribution in rills and the relationship between flow velocity and rill bed morphology. They showed that bed roughness increases with slope while flow velocity decreases. Flow velocity increases until a threshold Froude number between 1.3 and 1.7 is reached, and a hydraulic jump occurs leading to the formation of a pool. Govers (1992b) tested, in another laboratory flume, the relationship between discharge, flow velocity and flow area. He showed that mean flow velocity is not at the front of the water, but where the water reached 80–90% of its maximum width. The mean flow velocity and cross-sectional flow area can be related to discharge for rills eroding loose, non layered materials like agricultural soils. Soil characteristics and slope appear to be of minor importance in this study.

The main problem with these laboratory experiments is that the results cannot be easily transferred to natural rills. In the laboratory, flumes with compacted soil material are used, but Giménez and Govers (2002) showed that most of the data attained on rill models with smooth beds cannot be applied to naturally developed rills with rough beds. In many cases, hydraulic parameters are extracted from equations created to describe flow behaviour in rivers. Govers (1992a) and Govers et al. (2007) showed that these parameters cannot simply be transferred to flow behaviour in rills. This process oriented research needs also to be conducted in natural rills, using a mixture of process oriented (laboratory) experiments and field research.

However field research is often in pursuit of other targets. Experimental work is very rare. Interests are adjusted to catchment areas, long-term-observations on plots or, in best cases, the measurement of different parameters under natural rainfall. Some examples are given here.

De Santisteban et al. (2005) tested two different indices to characterize the influence of watershed topography on channel erosion. The first is defined as the product of watershed area and the partial area-weighted average slope. The other one is similar but uses the slope as the weighting factor, i.e. it is the product of watershed area and the length-weighted average slope. It was shown, that for a wide range of soil, climate, soil use and management conditions, the close relationship between soil erosion and topography can be quantified using the two indices. Govers and Poesen (1988) observed on a 7500 m^2 field plot the evolution of a rill and gully system. The periodic survey started on 15.11.1983 and finished at 3.10.1984. They measured detachment rates and used splash cups to get data about splash erosion. The sediment being detached by splash on inter-rill areas is transported to the channel system mainly by inter-rill wash. Rill and gully erosion is more important than inter-rill erosion, but the relative importance of inter-rill erosion varies in time and space, due to changes of the inter-rill surface characteristics and the activation of sidewall and gullying processes in the channel network. Bruno et al. (2008) accomplished field investigations under natural rainfall. They measured cross sections, runoff and soil loss and proposed a simple mathematical model for estimating soil loss. The analysis of the measured erosive events allowed establishment of the proportion of both rill erosion and inter-rill erosion on total soil loss. The measurements showed that rill erosion increases the total sediment transport efficiency because rill flow is able to transport both the inter-rill eroded sediments and sediment particles eventually detached from the rill wetted perimeter. The measurements also allowed verification of a relationship between rill length and rill volume, which was theoretically deduced by the dimensional analysis and self-similarity theory. This equation shows that rill length can be usefully employed as a severity index of the rilling process. The morphological evolution of the rill cross-section showed that in the first part of the rill length the channelized flow is able to erode the wetted perimeter and to transport the eroded particles, while in the terminal part of the rill the actual sediment load is high and the flow is only able to transport the particles coming from upstream without scouring the rill perimeter. The shear stress profile along the rill length confirmed that in the terminal part of the rill the flow is able to transport the upstream eroded sediment particles, but not able to detach additional material.

The review of the experimental research on rill erosion processes shows the weak and partially contradictory results of attempts to understand rill erosion processes. This can be seen in the large number of studies dealing with the relationships between flow parameters and particle detachment and transport. This is even clearer regarding the rills' development and behaviour in the field. There is still a lack of direct observation of the throughflow and sediment transport/detachment characteristics in natural rills. On the other hand, rills and their behaviour in the landscape can give insight to the main dominating soil erosion processes and their magnitude