IMPLICATIONS OF RECENT EXPERIMENTAL FINDINGS FOR RILL EROSION MODELING

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1. Introduction

Several relationships that describe flow hydraulics and sediment detachment within an eroding rill/gully have been proposed. Often, concepts were taken from literature on alluvial rivers and directly applied to these eroded channels. However, there are both similarities and discrepancies between flow and sediment detachment and transport in rivers (or gullies) and rills. Rills are small, concentrated flow paths where typical water depths are of the order of millimetres to several centimetres running over steep slopes. In such shallow flows, the effect of the bed topography on flow hydraulics cannot be neglected. In addition, rills actively erode and thus evolve morphologically over very short timescales. In contrast, water depth is usually much larger than the bed roughness in alluvial rivers (or gullies) and their morphological evolution is relatively slow. It can therefore be questioned whether concepts that were developed for rivers or big channels can directly be applied to rills. Rill flow and rill detachment experiments provide an opportunity to investigate to what extent the concepts used in models are a truly valid description of the erosion processes occurring. Field observations allow a further test of model concepts: a strong deviation between observed and predicted tendencies points to a significant deficiency in the model. Unfortunately, the reverse is not true: due to equifinality problems, good results can often be produced for the wrong reasons. The major aim of this paper is to critically review the theoretical concepts that are underpinning current models of rill flow and sediment detachment in the light of recent experimental results and, when necessary, to propose modifications to the theoretical formulations so that they are in agreement with experimental evidence. We also investigate to what extent a detachment model of reduced complexity, which is based on experimental observations, is consistent with field observation on the effect of topography on rill erosion.

2. Rill erosion models: an overview

Here, we present a description of both the hydraulic principles and the representation of detachment processes which are frequently used in current models.

Most erosion models use Manning's equation as a fundamental equation for the relationship between the velocity of water in a channel (m s^{-1}), v, and the geometry of that channel :

$$v = (R^{2/3} S^{1/2}) / n \quad (1)$$

Where, R = hydraulic radius (m); S = slope gradient (sin); n = Manning's number (s $m^{-1/3}$). The value of n is normally obtained by experimentation and is generally assumed to be independent of flow conditions. The different components of the hydraulic roughness are assumed to be additive. In order to calculate flow velocity and depth using flow resistance equations information on rill geometry is also needed. In most models values for geometric variables such as rill width are either provided by the user or are calculated using empirical relationships.

Several approaches have been used to estimate soil detachment in rills. Probably the most commonly used relationship to predict rill detachment capacity is based on the excess of shear stress (τ) over a critical value (τ_c) applied by the concentrated flow:

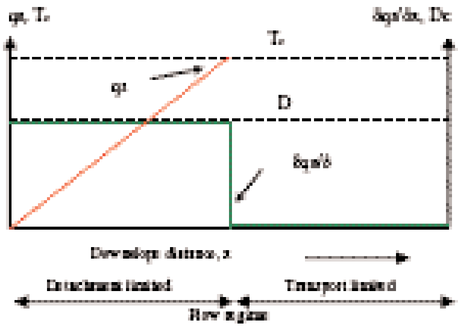

Fig. 1. Variation of sediment load with distance downslope assuming a constant discharge over a rectilinear slope (after Kirkby, 1980).

$$[Dr = K\,(a\,\tau - \tau_c)^b] \quad (2)$$

This assumes that sediment detachment (D_r) is a separate phase of the soil erosion process and that soil detachment is independent of the magnitude of the sediment load (q_s) (Fig. 1). Assuming a constant discharge over a rectilinear slope, sediment discharge will then increase linearly with distance downslope until sediment transporting capacity (T_c) is reached (Fig. 1). On the other hand, Foster and Meyer (1972) proposed a first-order detachment-transport coupling, which states that, the detachment rate (kg m^{-2} s^{-1}), Dr, is proportional to the difference between transporting capacity (kg m^{-1} s^{-1}), T_c, and sediment load (kg m^{-1} s^{-1}), q_s:

$$Dr = \delta q_s / qx = \alpha\,(T_c - q_s) \quad (3)$$

IV International Symposium on Gully Erosion. J. Casalí and R. Giménez (Eds.)
 ISBN 978-84–9769-198-7

Where, α = rate control constant (m^{-1}), x = distance (m). As sediment concentration increases downstream, detachment rate decreases accordingly. Under transport limited flow conditions the detachment rate is zero (Fig.2).

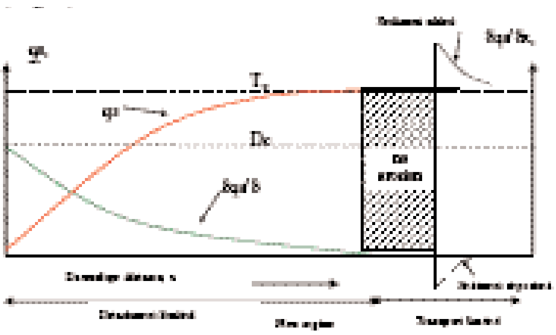

Fig. 2. Transport/detachment models following Foster and Meyer's approach. *Dc* = Detachment capacity (kg m^{-2} s^{-1}) (after Foster and Meyer, 1972).

3. Rill modeling: state of the art

Govers (1992) noticed that rill flow velocities tended to be independent of slope. This is due to a feedback between rill bed morphology and flow conditions that, besides, leads to a constant average (near-critical) Froude number (Giménez and Govers, 2001). This finding shows that assuming a constant hydraulic roughness [e.g., *n* in (1)] is clearly inappropriate for eroding rills. In addition, a simple power equation to estimate velocity, v (m s^{-1}) directly to discharge, Q (m^3 s^{-1}) and independent of slope was proposed by Govers:

$$v = 3.52\ Q^{0.294} \tag{4}$$

On the other hand, Giménez and Govers (2002) showed that several flow hydraulic parameters can be related to flow detachment. However, only if shear stress or the unit length shear force, Γ (kg s^{-2}) (5) is used to predict sediment detachment, it is possible to directly account for beds with different roughness.

$$\Gamma = \tau\ Wp \tag{5}$$

Where, Wp is wetted perimeter (m)

After making a correction, these variables can also be related to flow detachment when a vegetation or residue cover is present (Giménez and Govers, in press). Thus, these flow variables (i.e., τ, Γ) appear to be more 'universal' than other hydraulic variables which were used to predict sediment detachment. With respect to the formulation of the detachment-transport coupling model (3), recent findings (e.g., Giménez and Govers, 2002) show that flow detachment and sediment transport are not necessarily controlled by the same hydraulic parameters. This implies that sediment detachment cannot simply be described as a function of sediment transporting capacity deficit as is proposed in the original Foster and Meyer model (3). Other studies suggest that the effect of sediment load on detachment may be more important in high-energy flow conditions.

While it is clear that a full physical description of flow detachment and transport in rills is still beyond reach, we can use the available experimental information to construct a simple model of rill flow detachment:

$$\Gamma = \rho\ g\ (0.34\ Q^{0.732})\ S \tag{6}$$

In order to investigate to what extent this (6) is in agreement with field observations, a comparison with published data was made. We attained a good agreement between field observations and model predictions. This detachment model (6) is definitely too simple to be applicable in all circumstances, but at least it explains the basic relationship between erosion rate, slope gradient and discharge for rills eroding cohesive materials.

4. Conclusions

Currently used approaches to model rill flow hydraulics and sediment detachment in rills are not always in agreement with available experimental evidence. The experimental data that are at present available suggest that rill flow hydraulics is not well described by the Manning's equation. Furthermore, experimental data suggest that the Foster-Meyer model for sediment load and transport interaction may need modification. A simple model that can be proposed for sediment detachment in rills and that is consistent with experimental evidence relates sediment detachment per unit length to unit length shear force. The exponents for discharge and slope in the expression resulting from this analysis are in good agreement with field data. A simple expression such as the one derived in this paper is certainly not capable to describe sediment detachment in all cases, as it does not allow to take into account size-selectivity, nor the interaction between sediment load and sediment detachment. Care should be taken however that the behaviour of more sophisticated models is consistent with existing experimental data. Using models that are consistent with experimental data will not necessarily directly improve model performance. However, it may ultimately lead to models that are more generally applicable and also produce meaningful results outside of the domain for which original calibration and validation was carried out.

Acknowledgements: Rafael Giménez was funded by the Spanish Ministry of Education and Research (Juan de la Cierva Programme).

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