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Experiments for testing soil texture effects on flow resistance in mobile bed rills

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ABSTRACT

In this paper a recently theoretically deduced rill flow resistance equation, based on a power-velocity profile, was tested experimentally on plots of varying slopes and soil texture in which mobile bed rills are incised. Measurements of flow velocity, water depth, cross section area, wetted perimeter and bed slope conducted in rill reaches incised on experimental plots, having different slope values (9, 14, 22, 24 and 26%) and soil texture (clay fraction ranging from 42 to 73%), and literature data were used to calibrate the flow resistance equation. In particular, the relationship between the velocity profile parameter Γ, the channel slope, the flow Froude number and texture fractions was firstly calibrated using 147 rill reach data. Then this relationship was tested using 126 measurements carried out with soils having different texture (percentage of clay ranging from 9.6 to 73%) and slopes (6.9%–26%). The measurements allowed to establish that a) the Darcy-Weisbach friction factor can be accurately estimated using the proposed theoretical approach, and b) the data were supportive of the soil texture influence on rill velocity and flow resistance.

1. Introduction

Rill erosion is due to the detachment of soil particles and sediment transport by the channelized flow, but the rills also receive the runoff and sediment yield delivered from interrill areas (Bagarello and Ferro, 2004, 2010; Govers et al., 2007; Bruno et al., 2008; Bagarello et al., 2015; Di Stefano et al., 2013, 2015; Peng et al., 2015). Rill erosion is the main sediment source at hillslope scale and Mutchler and Young (1975) (Zhang et al., 2016) stated that > 80% of the eroded particles from hillslopes are transported in rills.

Several relationships that describe rill hydraulics within an eroding rill (Foster et al., 1984; Line and Meyer, 1988; Gilley et al., 1990; Govers, 1992; Abrahams et al., 1996; Takken et al., 1998; Hessel et al., 2003) have been proposed and many equations derived from literature on alluvial rivers have been applied (Govers et al., 2007). However, rill hydraulics may differ greatly from the hydraulics of flow in larger channels (Foster et al., 1984) since rills are small and ephemeral flow paths which are characterized by small flow depths (from millimeters to several centimeters) and bed topography characterized by steep slope values (Nearing et al., 1997; Peng et al., 2015).

A target of rill erosion modeling is an adequate study of rill flows (Abrahams et al., 1996) since their hydraulic conditions are very different from those found in large open channel flows (Nearing et al., 1997). Notwithstanding the difference between rills and rivers, classical hydraulic equations, such as Manning's and Chezy's equation, are often used in physically based models (Ferro, 1999; Govers et al., 2007; Powell, 2014; Strohmeier et al., 2014; Nouwakpo et al., 2016). Furthermore the uniform open channel flow equation could not be able to describe the flow moving in an eroding rill channel because of the interaction among rill flow, soil erosion and sediment transport (Nearing et al., 1997). In other words, the interaction among channelized flow, eroding rill channels and sediment transport affects the rill morphology and the hypothesis of fixed bed used by Chezy's equation cannot be applied.

Notwithstanding rill flow experiments can provide an opportunity (Wirtz et al., 2010, 2012, 2013) to verify if the concepts currently applied in soil erosion models are applicable (Govers et al., 2007), rill erosion measurements are still lacking (Stroosnijder, 2005; Wirtz et al., 2012) and there is a need to carry out field and laboratory experiments.

When a theoretical velocity distribution (Baiamonte et al., 1995; Ferro, 2003) can be applied to the velocity profiles measured in different verticals of the cross-section of flow (Ferro and Baiamonte, 1994), the integration along the cross-section of these velocity distributions allows one to deduce the flow resistance law.

The unavailability of velocity measurements is generally surrogated by the use of empirical flow resistance formulas (Ferro, 1999; Powell,

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2014):

$$V = C\sqrt{R\ s} = \frac{s^{1/2}\ R^{2/3}}{n} = \sqrt{\frac{8\ g\ R\ s}{f}} \tag{1}$$

in which V (m s^{-1}) is the cross-section average velocity, C (m$^{1/2}$ s^{-1}) is Chezy coefficient, n (m$^{-1/3}$ s) is Manning coefficient, f is Darcy – Weisbach friction factor, s is channel slope, R (m) is hydraulic radius and g (m s^{-2}) is acceleration due to gravity.

In most erosion models Manning's equation is applied as a basic relationship between flow velocity in the rill and the geometry of that channel. The Darcy-Weisbach friction factor is applied in WEPP (Water Erosion Prediction Project) (Foster et al., 1995; Govers et al., 2007).

However, there is a gap between the complex rill flow in nature and the simplified channel flow concepts which are used to establish the commonly applied flow resistance equations.

At present, the effect of slope gradient on flow velocity and roughness in rills is a topic subjected to scientific debate (Foster et al., 1984; Govers, 1992; Nearing et al., 1997; Giménez and Govers, 2001; Torri et al., 2012). Govers (1992) suggested a “feedback mechanism” to justify that velocity tends to be independent of slope for a flow in a mobile bed rill. According to this Author, the expected increase of flow velocity due to slope gradient is counterbalanced by the effect of the increase of erosion rate with increasing slope. This last effect produces an increase of bed roughness, thereby slowing the flow velocity. The increase of roughness with erosion rate is also confirmed by rill erosion experiments carried out by Xinlan et al. (2015) and the analysis developed by Torri et al. (2012). The absence of a slope effect on rill flow velocity is also reported by Nearing et al. (1997; 1999) and by the experimental runs which Takken et al. (1998) carried out with rills incised on an unconsolidated soil. Assuming as correct the slope independence hypothesis of rill velocity, the use of a constant hydraulic roughness coefficient for equations such as Darcy-Weisbach Eq. (1) could be inappropriate for eroding rills. In fact, Eq. (1) allows one to obtain a slope-independent rill flow velocity only if the value of Manning's n (Hessel et al., 2003) or the Darcy-Weisbach friction factor f increases with slope gradient.

For fixed bed rills, Foster et al. (1984) and Abrahams et al. (1996) experimentally tested that rill flow velocity increases with slope gradient. In particular, Foster et al. (1984) established that V increases with a power 0.48 of the slope gradient which confirms the applicability of Eq. (1) with a constant f value.

Runoff and erosion processes are affected by soil surface roughness which is a key parameter quantifying the irregularities of the soil surface caused by soil texture, aggregate size, rock fragments, vegetation cover and land management (Thomsen et al., 2015). Detailed information about soil roughness is still lacking for the difficulties due to soil microrelief measurements and the absence of a systematic research (Zhang et al., 2016). The soil type affects the micro-relief variations due to grain sizes and is responsible of the grain resistance which acts at the soil surface corresponding to the wetted rill perimeter.

Peng et al. (2015) have experimentally established that on slopes < 10° the friction factor f decreases gradually as the flow Reynolds number Re increases, while on steeper slopes (12–15°) f increases gradually with Re. For explaining this trend Peng et al. (2015) suggest that on gentle slope the roughness reduction (*grain resistance*) with Re is due to an increase of flow depth greater than the roughness increase caused by changes of sediment load and rill morphology. On steeper slopes, when the Reynolds number increases the flow velocity increases more than flow depth and *morphological* friction (as the one due to step-pool structures) controls flow resistance. In other words, rill friction factor value is due to grain-resistance and morphological (step-pools) resistance (Di Stefano et al., 2017d).

Progress in micro-topography observation technology (James and Robson, 2012; Gómez-Gutiérrez et al., 2014; Frankl et al., 2015; Micheletti et al., 2015; Di Stefano et al., 2017b; Westoby et al., 2012) have led to an increase in experimental work on rill morphology (Carollo et al., 2015; Vinci et al., 2015; Zhang et al., 2016; Di Stefano et al., 2017b).

In previous papers Di Stefano et al. (2017c, 2018), using the Buckingham's Theorem of the dimensional analysis and the self-similarity theory (Barenblatt, 1979, 1987), have deduced a theoretical resistance equation based on the integration of a power velocity profile. This theoretical flow resistance law has been tested by an experimental investigation carried out using reaches of erodible rills shaped on plots having different slope values s_p (9, 14 and 22%) (Di Stefano et al., 2017c, 2018) and characterized by a narrow range of soil texture.

In this paper, for a hydraulic condition in which the grain resistance is the prevailing friction mechanism, the results of an investigation on flow motion in rills shaped on soils having different textures (clay fraction ranging from 9.6 to 73%) are reported. The applicability of a theoretical approach of the rill flow resistance equation is supported by both field measurements of flow velocity, water depth, cross-section area, wetted perimeter and bed slope carried out in literature (Strohmeier et al., 2014; Peng et al., 2015; Di Stefano et al., 2017c, 2018) and independent measurements carried out in this investigation.

2. The theoretical flow resistance equation

Since the flow velocity distribution can be expressed by a functional relationship representing the examined physical process, in previous papers Di Stefano et al. (2017c, 2018) suggested that the Π-Theorem of the dimensional analysis and self-similarity theory can be usefully employed to deduce the rill flow resistance equation (Barenblatt, 1979, 1987, 1993; Ferro, 1997).

For a uniform turbulent open channel flow the velocity distribution along a given vertical can be expressed by the following functional relationship (Barenblatt, 1987, 1993; Ferro, 1997; Di Stefano et al., 2017c; Ferro and Porto, 2018):

$$\Pi = \frac{y}{u_*}\frac{dv}{dy} = \varphi\left(\frac{u_*\ y}{\nu_k}, \frac{u_*\ h}{\nu_k}, \frac{h}{d}\right) \tag{2}$$

in which v is the local velocity, y is the distance from the bottom, $u_* = \sqrt{g\ R\ s}$ is the shear velocity, ϕ is a functional symbol, h is the water depth, d is the bed particle diameter and ν_k is the water kinematic viscosity.

Assuming the Incomplete Self-Similarity (ISS) in $u_* y / \nu_k$ (Barenblatt and Monin, 1979; Barenblatt and Prostokishin, 1993; Ferro and Pecoraro, 2000; Ferro, 2017; Ferro and Porto, 2018), the following velocity distribution is obtained:

$$\frac{v}{u_*} = \Gamma\left(\frac{u_*\ y}{\nu_k}\right)^{\delta} \tag{3}$$

in which Γ is a function to be defined by velocity measurements and δ is an exponent which can be calculated by the following theoretical equation (Castaing et al., 1990; Barenblatt, 1991):

$$\delta = \frac{1.5}{\ln\ Re} \tag{4}$$

in which $Re = V\,h / \nu_k$ is the flow Reynolds number.

Integrating the power velocity distribution (Eq. (3)), the following expression of the Darcy-Weisbach friction factor f is deduced (Barenblatt, 1993; Ferro, 2017; Ferro and Porto, 2018)

$$f = 8\left[\frac{2^{1-\delta}\ \Gamma\ Re^{\delta}}{(\delta+1)(\delta+2)}\right]^{-2/(1+\delta)} \tag{5}$$

Setting $y = \alpha\ h$, the distance from the bottom at which the local velocity is equal to the cross-section average velocity V, from Eq. (3) the following estimate Γ_v of Γ is obtained (Ferro, 2017; Ferro and Porto, 2018):