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Deriving and evaluating hydraulics and detachment models of rill erosion for some calcareous soils

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ABSTRACT

Rill erosion plays an important role in the amount of soil detachment and the transport sediment load on hillslope. Quantification of the soil erosion requires a more precise understanding of the processes and development of rill erosion models. The objective of this study was to derive and evaluate hydraulics and detachment models of rill erosion in calcareous soils of northwestern Iran. Rill erosion experiments were carried out at 55 locations with three replications under field conditions. At each point, the rill plots were created with a 0.2 m width and 4 m length on agricultural soils. The inflow rates were 4, 12, 20 and 30 l min^{-1} with varying slope from 4 to 25.5%. The results indicated that all conditions of flow regimes including sub- and super-critical (laminar and turbulent) were observed in created rills by overland flow. The mean flow velocity and rill depth have been described well by flow rate and slope gradient, while rill width and flow depth have been explained well by flow rate. The prediction detachment rate by rill flow based on stream power model by non-linear regression yielded the best results (R^2 = 0.545 and RMSE = 0.00213 kg $m^{-2} s^{-1}$) for all combinations of slope classes. However, there are no significant differences between prediction accuracy of linear and non-linear models, when individual slope classes were considered.

1. Introduction

Soil erosion is a process of detachment of soil particles from the soil mass and their transport by erosive factors (Elliot and Laflen, 1993; Zhang et al., 2003; Wang et al., 2016). Physically soil erosion models often divide soil erosion according to the sediment source into two components: inter-rill and rill erosion (Wagenbrenner et al., 2010). However, eroded rills are usual major concentrators of surface flow in croplands where soil particles are non-layered and eroding loose at farming depth. The rills on agricultural soils rapidly adapted their bed topographic in response to flow and slope changes (Govers, 1992). On the other hand, concentrated flow is deeper, faster and more energetic than the shallow flow that happens in inter-rill areas. Therefore, it is necessary that attention is focused on modeling rill geometry and detachment rates especially on arid and semiarid calcareous soils conditions.

Two important sub-processes in rill erosion are the flow detachment erosion and sediment transport (Meyer et al., 1975). Foster and Meyer (1972) generated a function to describe rill erosion:

$$D_r = D_c\left[1 - \frac{q_s}{T_c}\right] \quad (1)$$

where D_r and D_c are detachment rate and detachment capacity (kg $m^{-2} s^{-1}$), respectively, q_s represents the rate of sediment load (g $m^{-1} s^{-1}$) and T_c represents sediment transport capacity (g $m^{-1} s^{-1}$). The maximum D_r happens when the q_s = 0 (Govers et al., 2007; Wang et al., 2016). There are numerous relationships for predicting soil detachment by rill flow within an eroding rill that used in soil erosion models (Wagenbrenner et al., 2010). The D_c based on the flow shear stress flow is usual relationship to predict soil detachment by concentrated (Govers et al., 2007). Eq. (2) is the following general form:

$$D_c = K_{HP}(HP - HP_c) \quad (2)$$

where K_{HP} is soil rill erodibility parameter, HP is hydraulic parameters and HP_c is the critical value below which no detachment occurs. HP can be shear stress (τ) (Nearing et al., 1997), stream power (Ω) (Hairsine and Rose, 1992; Elliot and Laflen, 1993), unit stream power (Ωu) (Morgan et al., 1998) and unit length shear force (Γ) (Giménez and Govers, 2002). The τ, Ω, Ωu and Γ parameters were calculated as:

$$\tau = \gamma R_h \sin[\tan^{-1}(S)] \quad (3)$$

where γ is water specific weight (N m^{-3}), R_h is rill hydraulic radius (m), and S is slope gradient (m m^{-1}) (Nearing et al., 1997).

$$\Omega = \gamma R_h V \sin[\tan^{-1}(S)] \quad (4)$$

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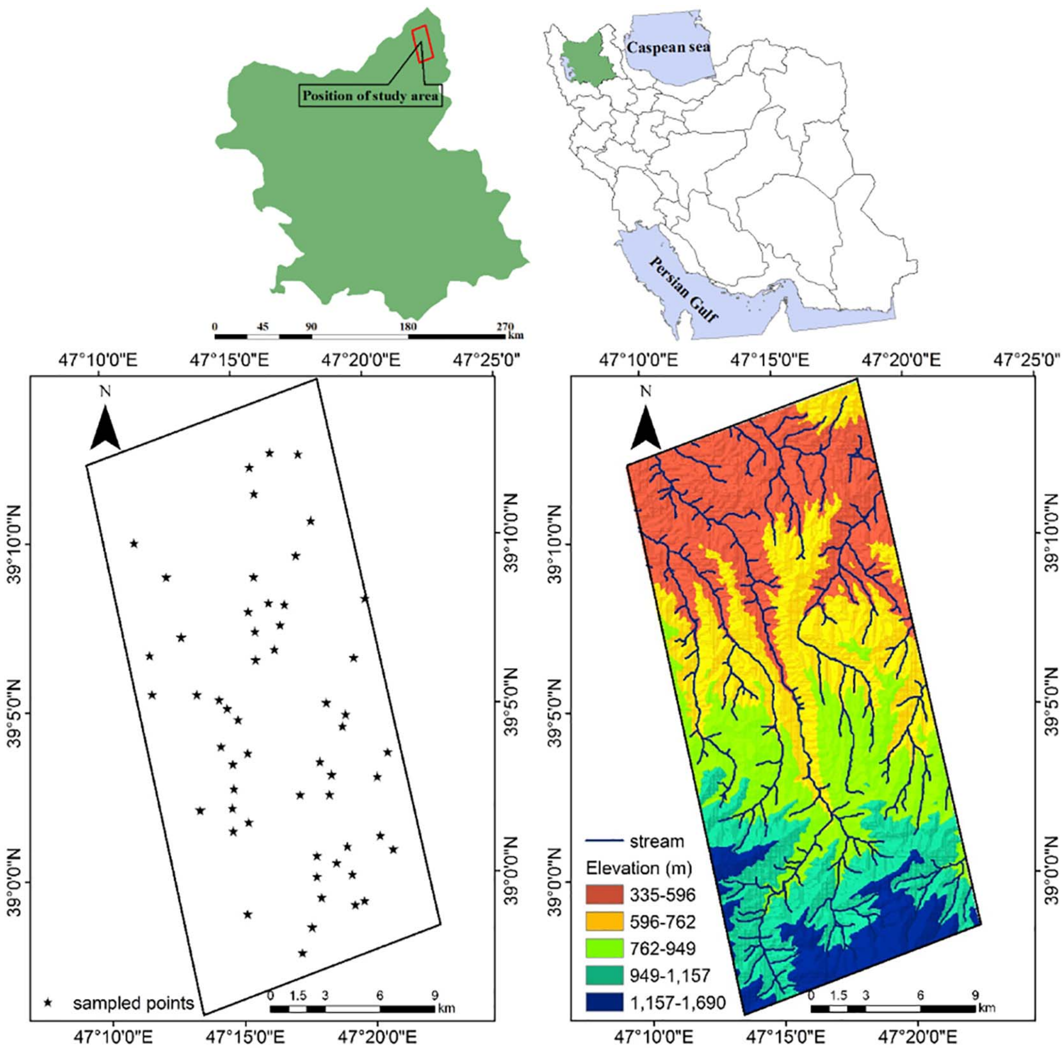

Fig. 1. Location of study area northwest Iran and distribution of studied points.

where V is the measured runoff velocity ($m\,s^{-1}$) (Bagnold, 1966).

$$\Omega u = V\sin[\tan^{-1}(S)] \quad (5)$$

(Yang, 1972).

$$\Gamma = \gamma A\sin[\tan^{-1}(S)] \quad (6)$$

where A is the rill cross-sectional area (m^2) (Giménez and Govers, 2002).

Nearing et al. (1991) indicated that shear stress and stream power were unsuitable predictors to estimate the soil detachment rate. They found out that there was a logarithmic function between the dependent variable (soil detachment) and independent variable (flow depth, bed slope and mean weight diameter of the aggregates) on silt loam soil. McIsaac et al. (1992) showed unit stream power was the best predictor to predict soil detachment by concentrated flow. Elliot and Laflen (1993) showed that the stream power model was highly efficient to describe the detachment capacity rate on the 36 sites with a wide range of geological, geomorphic, and geochemical properties from the WEPP model database. Nearing et al. (1997, 1999) reported that both shear stress or stream power were better suited to predict detachment rate and concluded the stream power-based detachment model was favored on silt loam and sandy loam soils. Zhang et al. (2003) showed that the stream power by a power function was the best predictor to estimate detachment rate at shallow flow conditions on the two silt loam soil from rangeland and cropland. Giménez and Govers (2002) indicated the superiority of the unit length shear force-based detachment model on silt loam and loamy sand soils with rough and smooth beds. Wagenbrenner et al. (2010) compared rill erosion models in two disturbed forest soils in the USA. It was observed that the stream power was a feasible and reliable predictor. Similar results were also observed for rangeland sites (Al-Hamdan et al., 2012). Li et al. (2015) quantified land use effects on soil detachment in the Loess Plateau. In this study, the detachment capacity was predicted by stream power, slope gradient, soil bulk density, median diameter, silt content, cohesion, and root density parameters. Wang et al. (2016) showed, in a loessial soil, detachment predictions by flow velocity, unit energy and stream power were better, but shear stress and unit stream power based detachment models presented poor results. These contrasting results to determine the best hydraulic parameter for estimating soil detachment rate by concentrated flow could be a result of different conditions at the studied sites.

It is clear that flow hydraulic parameters (i.e. τ, Ω, Ωu and Γ) are functions of the flow velocity, flow depth, rill depth, rill width and slope gradient. The results of more studies show that flow and rill geometry (flow depth, flow velocity, rill depth and rill width) are related to the corresponding flow discharge for concentrated flow, but the relationships are varied in the studies. Early research by Meyer et al. (1975) and Lane and Foster (1980) found that flow velocity and rill width predicted well from flow discharge. Gilley et al. (1990) using a nonlinear regression method, predicted rill width from flow discharge. Govers (1992) found that mean flow velocity depends on flow