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Analytical method for determining rill detachment rate of purple soil as compared with that of loess soil

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ABSTRACT

Rill detachment is an important process in rill erosion. The rill detachment rate is the fundamental basis for determination of the parameters of a rill erosion model. In this paper, an analytical method was proposed to estimate the rill detachment rate. The method is based on the exact analytical solution of rill erosion to the differential equation of rill detachment. The rill sediment concentration distribution as a function of rill length was identified through laboratory experiments under different slope gradients and flow rates. The sediment concentration processes from experiments on loess and purple rills were considered to estimate the rill detachment rates of both soils analytically. They were respectively used as a function of rill length and sediment concentration. The analytical detachment rates were compared with the numerically determined values to verify the analytical methods. The rill detachment rates of the two soils under different flow rates and slope gradients estimated by the analytical method were further compared on the basis of detachment-sediment function and detachment-rill length function. Results indicated that the analytically estimated values were very close to the numerically estimated values. Numerical and analytical methods were equally useful for rill detachment rate estimation. Therefore, the analytical method was verified to be rational and applicable for the rapid determination of the rill detachment rates based on either sediment concentration or rill length. The analytical detachment values of purple and loess soils suggested that the detachment rates of loess soil were significantly and considerably higher than those of purple soil. The erosion potentials of loess soil were also significant higher than those of purple soil. The differences in the erosion of the two soils decreased as the slope gradient and flow rate increased. These observations implied that the degree of loess soil erosion was greater than that of purple soil erosion at low slope gradients and flow rates. The factors causing these differences may be determined in terms of the properties of the two soils. Therefore, the proposed analytical method, in addition to the concepts and direct relationship to erosion process, could be applied to obtain the rill detachment rate for the determination of rill erosion model parameters.

1. Introduction

In soil erosion research, hillslope is an area where soil erodes and accumulates (Cochrane and Flanagan, 1997; De Baets et al., 2006; Khanbilvardi and Rogowski, 1986; Knapen et al., 2008). As a basic constituent unit of basins, hillslope is regarded as the beginning of research on soil erosion. Rill erosion is a significant step of soil slope erosion (Chen et al., 2015). As escarpments and water scouring form on an eroding slope, rills gradually develop. Soil detachment is a dynamic erosion process by which soil particles move from a soil parent material in response to erosion force. Rill erosion decreases the soil fertility and tillability (Chen et al., 2016). The rill detachment rate is a relevant indicator of rill erosion (Huang et al., 1996; Wilson, 1993; Zhang et al., 2002).

The rill detachment rate has been extensively investigated. Several hydraulic parameters, such as slope gradient, flow rate, flow depth, and sediment concentration, of overland flow significantly influence rill detachment (Govers et al., 1990; Cochrane and Flanagan, 1997; Nearing et al., 1999; Zhang et al., 2002, 2003). Nearing et al. (1997) examined the quantitative relationships of the rill detachment rate, runoff depth and slope gradient through variable slope experiments. Niu et al. (2013) evaluated the relationship between sediment supply and output and observed that rill detachment is relatively independent of the actual sediment

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discharge. Li et al. (2002) determined that the relationship between the rill detachment rate and energy loss of water flow on a slope surface by conducting soil flume scouring experiments. Rill erosion is considered in studies that incorporate overland flow erosion in process-based water erosion models, such as CREAMS (Knisel, 1980), WEPP (Nearing et al., 1999), EUROSEM (Morgan et al., 1992), and EGEM (Woodward, 1999). Among these models, WEPP is the most reliable water erosion physical model. Gilley et al. (1990) showed that WEPP simulation fails to consider rill occurrence and development under different rainfall conditions, water flow, and slope gradient. Stople, 2005 obtained research results to address this problem on WEPP. Further studies have been performed on rill erosion models.

Different relationships of soil detachment with overland flow are considered in soil erosion models to estimate the initiation and rates of erosion by scouring in rills (Zhang et al., 2013). In general, detachment rate calculation methods are numerical and analytical. Numerical methods are used to calculate the detachment rate based on experimental data. Experiments have been performed to determine the relationship between the rill detachment rate and other parameters. Analytical methods are employed to calculate the detachment rate based on fitting parameters. Numerical methods have been widely explored. For example, Moore and Burch (1986) examined the patterns of the detachment rate that changes with sediment load. Laboratory and field experiments have revealed that hydraulic parameters of water flow are closely related to the process of soil detachment by overland flow (Poesen et al., 2003; Knapen et al., 2007a,b). Lei et al. (2001) conducted laboratory experiments to evaluate the detachment rate of loess soil and found that the fitting parameters of the detachment rate change with rill length and sediment concentration. Lei et al. (2002a,b) further performed experiments related to the detachment rate to acquire other fitting parameters, which were used to infer analytical equations. Analytical methods have been proposed to assess the detachment rate and verify the experimental results theoretically.

Purple soil and loess soil are easily eroded. Rill detachment in the two soils has been extensively examined. In previous studies, analytical methods have been employed to evaluate loess soil. Hence, experimental results on purple soil should be verified. The fitting results of the detachment rate that changes with sediment concentration and rill length are essential for studies involving rill erosion models. The soil texture of purple soil is different from that of loess soil. Therefore, purple and loess soils should be compared using the analytical method.

2. Materials and methods

The sediment concentration along an eroding rill is distributed exponentially as Eq. (1)]:

$$c = A(1 - e^{-Bx}) \tag{1}$$

where c is the sediment concentration as a function of rill length, kg m^{-3}; A is the maximum sediment concentration at sediment transport capacity, kg m^{-3}; and B is the decreasing rate of sediment increase in water flow, m^{-1}.

The rill detachment rate is defined as the amount of soil that eroded from a unit area during a unit time (Nearing et al., 1991, 1997; Merten et al., 2001; Gimenez and Govers, 2002). On the basis of this concept and the erosion function defined by Eq. (1), rill detachments rate can be analytically computed.

Sediment concentration increases with rill length increasing because of the detachment of soil from the rill bed. The sediment concentration of c at the rill location x increases to $c + \Delta c$ at $x + \Delta x$ after the rill length increases (Δx) and the sediment concentration increases (Δc). Accordingly, the sediment load increases from cQ to $(c + \Delta c)Q$ and the rill width changes from w to $w + \Delta w$. The surface area of the rill segment from x to $x + \Delta x$ is estimated as $(w + w + \Delta w)\ \Delta x/2 = \Delta x(w + \Delta w/2)$. The average detachment rate of the rill segment Δx is estimated as follows:

$$D_r = \lim_{\Delta x \to 0}\left(\frac{(c + \Delta c - c)Q}{\Delta x(w + \Delta w/2)}\right) \approx \frac{\Delta cq}{\Delta x} \tag{2}$$

where x is the rill location, m; c is the sediment concentration, kg m^{-3}; Q is the flow rate, m^3 s^{-1}; w is the rill width, m; $Q = wq$ is the rill flow rate, m^3 s^{-1}; q is the unit-width discharge rate, m^2 s^{-1}; and D_r is the rill detachment rate, kg m^{-2} s^{-1}. Eq. (2) is the formula to numerically compute rill-detachment rate.

As Δx approaches 0, $\Delta w/2$ becomes 0. Thus, Eq. (2) is rewritten as follows:

$$D_r = \lim_{\Delta x \to 0}\frac{\Delta c}{\Delta x}\cdot\frac{Q}{w} = \frac{dc}{dx}q \tag{3}$$

Eq. (3) defines the analytical method to compute rill-detachment rate. Substituting Eq. (1) into Eq. (3) yields the computational method to analytically estimate the detachment rate as a function of rill length:

$$D_r = ABqe^{-Bx} = ae^{-Bx} \tag{4}$$

where a (kg m^{-2} s^{-1}) is the maximum analytical detachment rate, at the beginning when $x = 0$, and B is the decreasing rate of detachment rate, m^{-1}.

Eq. (4) can be rewritten by using Eq. (1) to obtain the analytical method that relates the rill detachment rate to sediment concentration:

$$D_r = ABq - ABq(1 - e^{-Bx}) \tag{5}$$

$$D_r = ABq - Bqc = d + ec \tag{6}$$

where d (kg m^{-2} s^{-1}) is the maximum detachment rate and e (m s^{-1}) is the proportionality coefficient that indicates the decreasing rate of the rill detachment rate as the rill sediment concentration increases.

Eq. (4) is used to compute the rill-detachment rate as a function of rill length. Eq. (6) is adopted to calculate the rill-detachment rate as a function of sediment concentration. In accordance with Eqs. (4) and (6), the rill detachment rate can be calculated analytically and directly from the sediment-rill relationship when the function between sediment concentration and rill length is defined, such as Eq. (1).

The experimental data sets reported by Chen et al. (2015) are used to verify the method and to determine detachment rate as a function of rill length or sediment concentration. Their experiments on rill erosion involved five slope gradients (5°, 10°, 15°, 20° and 25°) and three flow rates (2, 4 and 8 L min^{-1}). The experimental sites of the two soils were shown in Fig. 1. The sediment concentration from the eroding rills with different lengths from the rill inlet were determined by Chen et al. (2015).

It is very meaningful that the five slope gradients and three flow rates were chosen. First of all, the 25° is determined to be the critical slope gradient of returning farmland to forest in China. Therefore, the steepest slope gradient of a farmland in China is possibly to reach 25°. Then the designed five slope gradients covered the whole range wherein rill erosion may occur in the cultivated hillslope land. Secondly, the flow rates were chosen to cover a wide range of rainfall intensities of the study region. Rill erosion in the WEPP model uses a hypothesis that there is one rill or two rills every 1 m width of hill slope. For a standard runoff plot of 20 m long, a slope of 0.5 m wide produce about 100 L/h runoff under 10 mm/h net rainfall intensity, which is approximately equal to