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Evaluation of GUEST and WEPP with a new approach for the determination of sediment transport capacity

Majid Mahmoodabadi [a,*], Hossein Ghadiri [b,1], Calvin Rose [b,2], Bofu Yu [b,3], Hosseingholi Rafahi [c], Hassan Rouhipour [d]

[a] Dep. of Soil Sci., Agriculture Faculty, Shahid Bahonar University of Kerman, P.O. Box. 76169133, Kerman, Iran
[b] Faculty of Environmental Sciences, Griffith University, Nathan, Qld 4111, Australia
[c] Dep. of Soil Sci., Agriculture Faculty, University of Tehran, Karaj, Iran
[d] Research Institute of Forests and Rangelands, P.O. Box. 13185-116, Tehran, Iran

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SUMMARY

Sediment transport capacity (T_c) is a key parameter for all process-based erosion models. The objective of this study was to develop a new approach for accurate determination of T_c under infiltration conditions based on rill morphology and the sediment feedback relationship. This would allow the way in which sediment transport capacity is computed in WEPP and GUEST models. Six-m long rills in three soils were subjected to constant inflow rates (50, 75 and 122 ml s^{-1}) and three flume slope gradients (2%, 4% and 6%). Cross-sections of rills were measured precisely at 0.5 m intervals using a profile-meter prior to and after each experiment. The cumulative net rates of erosion at the end of each section were converted to sediment load along the rill length. The sediment feedback relationship was applied to fit the sediment load values and T_c was determined asymptotically under equilibrium conditions. The results showed that under infiltration conditions, both models tended to under-estimate T_c, however, T_c predicted using the GUEST model had better agreement with the measured T_c values than that predicted with WEPP. Using the proposed value of $F = 0.15$, the performance of GUEST in predicting T_c could be further improved. Sidewall slumping was found to be a plausible explanation for underestimation of T_c by WEPP, which is not explicitly modeled. In contrast, GUEST takes into account any observed changes in rill morphology. The results also indicated that T_c increased as a function of flow discharge and slope gradient, but was more sensitive to slope gradient than to flow discharge. Moreover, stream power was found to be a better predictor of T_c than shear stress. Yet, regression equations using unit discharge and slope gradient as independent variables, did not achieve any better estimation of T_c than did the GUEST (when $F = 0.15$). Accurate determination of parameter(s) used in a process-based model such as GUEST will lead to improved T_c estimations. Furthermore, T_c is a process-based parameter which should not ideally be estimated with regression equations.

1. Introduction

The understanding of soil erosion processes for developing process-based erosion prediction models has stimulated researchers to investigate new ways of estimating the sediment transport capacity (T_c) of overland flows (Nearing et al., 1997; Huang et al., 1999; Tayfur, 2002; Polyakov and Nearing, 2003). Sediment transport capacity is the maximum sediment load that a flow can carry and therefore, its accurate estimation is critical to developing process-based soil erosion models (Zhang et al., 2009). Sediment transport capacity is primarily a function of flow hydraulics (Zhang et al., 2011). It is also strongly influenced by sediment properties, such as sediment size, density, shape and roughness (Guy et al., 2009b; Nord et al., 2009). The size selectivity of overland flow (Issa et al., 2006) indicated that the T_c corresponding to a particular flow is strongly affected by sediment size.

In some studies, the suitability of different transport capacity equations has been assessed for overland flow conditions (Hessel and Jetten, 2007; Nord and Esteves, 2007; Ali et al., 2013). In this regard, the performance of selected transport capacity functions

* Corresponding author. Tel.: +98 341 3202651; fax: +98 341 3222043.
E-mail addresses: mahmoodabadi@uk.ac.ir (M. Mahmoodabadi), H.Ghadiri@griffith.edu.au (H. Ghadiri), c.rose@griffith.edu.au (C. Rose), b.yu@griffith.edu.au (B. Yu), hrafahi@yahoo.com (H. Rafahi), rouhi@rifr-ac.ir (H. Rouhipour).
[1] Tel.: +61 7 3735 5175.
[2] Tel.: +61 7 3735 7397.
[3] Tel.: +61 7 3735 7486.

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evaluated under different hydraulic and sediment conditions. Ali et al. (2013) examined the suitability of five widely used transport capacity equations under overland flow conditions. They found that none of the predictions with the existing functions was in good agreement with measured results, especially at low flow rates. Their results showed that the selected functions reasonably estimate T_c only under those ranges of conditions for which they were formulated. However, the degree of accuracy of the results varied substantially with grain size. In fact, many equations are valid only for specific ranges of sediment size and density (Guy et al., 2009a). Hessel and Jetten (2007) evaluated the suitability of eight transport equations using data obtained from steep slopes. They found that most equations were too sensitive to slope gradient and the T_c values were over-predicted for steep slopes. Also, they obtained large discrepancies between measured and predicted values of T_c with the Yalin (1963) equation. The possible reason for the differences was that they conducted experiments by using other slope gradients and bed materials as compared to the conditions for which experiments were conducted.

In recent decades, two alternative approaches have been developed for modeling water erosion and deposition. The first approach is based on the notion of sediment transport capacity (Foster and Meyer, 1972; Foster, 1982), and this has been implemented in several process-based erosion models such as WEPP (Nearing et al., 1989; Foster et al., 1995), EUROSEM (Morgan et al., 1998), CREAMS (Foster et al., 1980), and LISEM (de Roo et al., 1996). This modeling approach assumes that soil detachment only occurs when sediment load (q_s) is less than T_c and sediment deposition occurs if T_c is exceeded (Nearing et al., 1989; Yu, 2003). Another approach is based on the concept of simultaneous erosion and deposition processes implemented in the GUEST model (Rose et al., 1983a,b,c; Rose, 1985; Hairsine and Rose, 1991; Rose et al., 1997; Rose et al., 2007). In this model, the continuous processes of rainfall detachment, flow detachment, and sediment deposition are considered, simultaneously (Hairsine and Rose, 1992a,b). Net erosion or deposition is a result of the dynamic interactions among all the processes involved (Yu, 2003). The WEPP model has been applied and tested for runoff and soil loss prediction outside the United States (e.g. Yu et al., 2000; Yu and Rosewell, 2001; Gronsten and Lundekvam, 2006; Singh et al., 2011; Mahmoodabadi and Cerda, 2013).

A comprehensive analysis of the erosion and deposition equations was performed by Yu (2003) to identify and clarify the similarity and differences between the two frameworks. It was found that under steady-state conditions, the applied equations in WEPP and GUEST are structurally identical. The equations differ only in the way in which rainfall and flow detachments and sedimentation terms are formulated, and both require the sediment concentration at the transport limit (Yu, 2003).

A review of literature suggests that there is no study yet to compare how sediment transport capacity is determined in WEPP and GUEST. The objectives of this study were (1) to offer a new approach for the determination of the sediment transport capacity based on rill morphology changes along the rill length and the sediment feedback relationship, (2) to evaluate the WEPP and GUEST models in estimating sediment transport capacity, and (3) to examine the effects of flow discharge and slope gradient and the resultant stream power on the sediment transport capacity in concentrated rill flow.

2. Material and methods

2.1. A brief description of WEPP and GUEST

In WEPP, soil erosion is conceptually divided into interrill and rill erosion. Rill erosion is mainly caused by concentrated overland flows. When $q_s \leqslant T_c$, steady-state rill erosion is modeled in WEPP (Nearing et al., 1989) as:

$$\frac{dq_s}{dx} = D_c\left(1 - \frac{q_s}{T_c}\right) \tag{1}$$

where q_s is sediment load (kg m^{-1} s^{-1}), x is distance downslope (m), D_c is detachment capacity (kg m^{-2} s^{-1}), and T_c is sediment transport capacity (kg m^{-1} s^{-1}). Eq. (1) was primarily based on the sediment feedback relationship (Zhang et al., 2005), which was initially proposed by Foster and Meyer (1972) as:

$$\frac{D_r}{D_c} + \frac{q_s}{T_c} = 1 \tag{2}$$

where D_r is rill erosion rate (kg m^{-2} s^{-1}). Several studies have substantiated that the assumed sediment feedback relationship used in the WEPP model is reasonable for simulating soil detachment in rills (Cochrane and Flanagan, 1997; Lei et al., 2002; Zhang et al., 2005).

When $q_s > T_c$, net deposition occurs in rills. Deposition is modeled in WEPP through another equation. The paper is focused on soil detachment in rills as the dominant erosion process, the sediment deposition equation used in WEPP was thus not considered in this paper. In the WEPP, the sediment transport capacity is determined using the shear stress as:

$$\tau = \rho g S R \tag{3}$$

where ρ is the density of eroding fluid (kg m^{-3}), g is the acceleration due to gravity (m s^{-2}), S is the slope gradient, and R is the hydraulic radius (m). In the WEPP model, sediment transport capacity is estimated with the Yalin's equation (Yalin, 1963; Nearing et al., 1989).

The initial theory of the GUEST model was established by Rose et al. (1983a,b) and its hydrological component was described by Rose et al. (1983c) through the kinematic flow approximation. This approach has received experimental support (Proffitt et al., 1991; Proffitt et al., 1993; Huang et al., 1999; Yu and Rose, 1999; Yu et al., 1999). For rill erosion, GUEST assumes that the entrainment and re-entrainment by flow, and concurrent sediment deposition are the dominant processes which collectively control the sediment concentration (c). In the case of net erosion, the equilibrium condition, when the transport capacity is achieved and maintained, requires that the rate of deposition equals the rate of re-entrainment (Hairsine and Rose, 1992b). Thus, sediment concentration at the transport limit (c_t) can be determined as (Misra and Rose, 1996):

$$c_t = \frac{R_1 F}{v_a}\left(\frac{\sigma}{\sigma - \rho}\right)\left(\frac{\Omega - \Omega_0}{f_r g D}\right) \tag{4}$$

where c_t is the sediment concentration at the transport limit (kg m^{-3}), R_1 is the ratio of sediment layer width to the wetted perimeter, F is the fraction of stream power effective in entrainment and re-entrainment, v_a is the weighted average settling velocity (m s^{-1}), σ is the wet density of sediment (kg m^{-3}), ρ is the water density (kg m^{-3}), Ω and Ω_0 are stream power and threshold stream power per unit area (W m^{-2}), respectively, f_r is a dimensionless parameter calculated through the sidewall slope of rill, and D is water depth (m). Unlike WEPP, the main hydraulic variable is the stream power in the GUEST, which is calculated as:

$$\Omega = \tau V \tag{5}$$

where V is the mean flow velocity (m s^{-1}).

2.2. Soil sampling and analysis

Three cropland top soils (0–20 cm) with different particle size distributions were taken from the field for this study. Some