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Suitability of transport equations in modelling soil erosion for a small Loess Plateau catchment

Rudi Hessel *, Victor Jetten [1]

Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O.Box 80.115, 3508 TC Utrecht, The Netherlands

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Abstract

Erosion models have not often been applied to very steep terrain such as the gully catchments of the Chinese Loess Plateau. The purpose of this research was to evaluate the suitability of a number of transport equations for use in erosion modelling under Loess Plateau conditions. To do this the equations were programmed into the LISEM model, which was applied to the 3.5 km^2 Danangou catchment in the rolling hills region of the Loess Plateau. Previous evaluations of transport equations used either flume tests or river sections, and did no spatial modelling. The results show that some equations predicted physically impossible concentrations (defined as above 1060 g/l). The results were evaluated by using two methods: 1) by comparing predicted and measured sedigraphs and sediment yield at the catchment outlet, and 2) by comparing the fraction of the catchment in which physically impossible transport capacities occurred. The results indicated that for the small grain sizes, high density flows and steep slopes of the gully catchments on the Loess Plateau the Shields parameter attained very high values. Furthermore, the transport threshold can usually be neglected in the equations. Most of the resulting equations were too sensitive to slope angle (Abrahams, Schoklitsch, Yalin, Bagnold, Low and Rickenmann), so that transport rates were overpredicted for steep slopes and underpredicted for gentle slopes. The Yang equation appeared to be too sensitive to grainsize. The Govers equation performed best, mainly because of its low slope dependency, and is therefore recommended for erosion models that simulate sediment transport by flowing water in conditions with small grain sizes and steep slopes.

Keywords: Transport capacity; Chinese Loess Plateau; Soil erosion modelling; Sediment concentration; Steep slopes; Small grain size

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1. Introduction

Sediment transport is an important process in catchment soil erosion as it determines the amount of soil removed. In the rolling hills region of the Chinese Loess plateau water is both the major cause of erosion and the agent of sediment transport. Water can transport sediment in the form of bedload and suspended load. Water flow is also often subdivided in overland flow and channel flow (or streamflow), which is a distinction that is relevant to sediment transport as well. There are several differences between streamflow and overland flow:

- Overland flow is much shallower. Shallow flow exhibits undulation, so that flow conditions are changing continuously (Alonso et al., 1981; Singh, 1997).

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* Corresponding author. Currently at: Soil Science Centre, Alterra, Wageningen University and Research Centre, P.O.Box 47, 6700 AA Wageningen, The Netherlands. Tel.: +31 317 486530; fax: +31 317 419000.

E-mail address: rudi.hessel@wur.nl (R. Hessel).

[1] Currently at: ITC, P.O. Box 6, 7500 AA Enschede, The Netherlands. Fax: + 31 53 4874436.

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- Overland flow is much more influenced by surface roughness and raindrop impact (Alonso et al., 1981; Singh, 1997; Abrahams et al., 2001).
- Saltation and even suspension might be limited in overland flow because of the small flow depth, so that bedload transport is likely to be the dominant mode of transport (Julien and Simons, 1985; Singh, 1997).
- In upland areas soil surfaces are usually more cohesive than in alluvial channels (Singh, 1997).
- Overland flow is often laminar, while streamflow is usually turbulent (Julien and Simons, 1985).
- Slopes are usually much steeper in the case of overland flow than in the case of streamflow (e.g. Govers, 1992).

Slope steepness and discharge are probably the most important controlling factors in sediment transport. Both are very different for streamflow and overland flow.

Many empirical equations to predict transport capacity have been developed. Most equations predict transport from a combination of flow velocity, discharge, water depth, energy slope and particle characteristics. These equations can be subdivided in bed load equations and total load equations, but also in overland flow equations and channel flow equations. Flume experiments have often been used to derive the equations. As Beschta (1987) noted each equation has usually been developed for a limited range of conditions and when applied under field conditions, the estimated transport rates for the different equations may vary over several orders of magnitude. One should thus be very cautious to apply these equation to conditions outside those for which they were developed, such as using channel flow equations to overland flow conditions and vice versa. Equations developed for streamflow have nevertheless been applied to flow on plots without concentrated flow. A reason for this is that the number of transport equations that have been developed for channel flow is much larger than that for overland flow. Some transport equations for interrill flow are available (e.g. Everaert, 1991; Huang, 1995), but these equations were developed using extremely small laboratory plots that might not be representative for field conditions either. Besides, for catchments, both overland flow and concentrated flow are likely to occur.

Several authors (Alonso et al., 1981; Low, 1989; Govers, 1992; Guy et al., 1992) have tested the performance of a number of different equations on their data set before. Often, channel flow equations were evaluated for their performance in the case of overland flow. Other authors (Julien and Simons, 1985; Prosser and Rustomji, 2000) reviewed a large number of available transport equations on theoretical grounds. They reason that discharge (q) and slope (S) are the basic controlling factors and that other parameters such as shear stress, stream power are derived from these two basic parameters. Therefore, expressing all equations in terms of q and S will make comparison possible.

All studies mentioned above tested different sets of transport equations, using different methods, and reached different conclusions about what the most suitable transport equation is. The studies also reached different conclusions about the applicability of channel flow equations to overland flow. In several cases, the most suitable equation proved to be one developed by the author himself. This implies that the suitability of an equation depends on the local conditions. For certain equations there are some known limits of application, e.g. the Ackers–White equation is apparently unsuitable for fine sediments (Van den Berg and Van Gelder, 1993). In most cases such limits are not known beforehand and the applicability of any particular equation can only be evaluated by testing it for the local circumstances. This means that the choice for any particular equation is mainly pragmatic and based on performance rather than on theoretical considerations.

In theory, the equations discussed in this paper are not transport *capacity* equations, but transport equations. In practice this amounts to the same thing since most equations suppose cohesionless materials. Therefore, the transport rate is determined by fluid conditions instead of sediment availability. On the Loess Plateau the soils are cohesive. The actual transport rates are therefore likely to be lower than those predicted by the transport equations. Thus, the transport equations can safely be applied as if they were transport capacity equations.

Sediment transport was studied as part of an erosion research project in the Danangou catchment, a typical small (3.5 km^2) Loess Plateau catchment in Northern China with steep slopes and a loess thickness close to 200 m (Fig. 1). The soils are mainly erodible silt loams that classify as Calcaric Regosols/Cambisols in the FAO-system (Messing et al., 2003). Median grain size of the loess is about 35 μm. The Loess Plateau is a region of extreme sediment concentrations; concentrations of 1000 g/l are reported regularly (Jiang Deqi et al., 1981; Zhang et al., 1990; Zhaohui Wan and Zhaoyin Wang, 1994). Even higher concentrations can sometimes occur. In the Danangou catchment water samples taken during a number of events revealed concentrations of up to 500 g/l. The climate is semi-arid, with occasional heavy thunderstorms in summer. On average