The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2444-20

College on Soil Physics - 30th Anniversary (1983-2013)

25 February - 1 March, 2013

The streampower concept in estimating sediment transport

GABRIELS Donald Maurice
University of Ghent Laboratory of Soil Physics
Fac. Agric.& Appl. Biol.Sciences, Dept. of Soil Management, Coupure Links 653,
B-9000 Ghent
BELGIUM

The streampower concept in estimating sediment transport

Donald Gabriels

UNESCO Chair on Eremology, Department of Soil Management, Ghent University, Belgium donald.gabriels@UGent.be

1. Introduction

Numerous experiments have been carried out on laboratory and on field plot scale to assess the different subprocesses and factors involved with soil erosion. In view of this some assumptions are made that experimentally obtained equations and/or relationships can be used to simulate the complex erosion process at the hillslope and/or (micro) watershed level.

Erosion occurs when the erosive forces, represented by the momentum flux of the raindrop impact and the momentum flux of the overland flow, exceed the cohesive forces between the soil particles and the downward component of the turbulent overland flow. Under field conditions the sediment transport is limited by the transport capacity of the flow. The factors which influence the transport capacity are the settling velocity of the soil particles and the vertical component of the turbulent overland flow. On very cohesive surfaces, sediment transport is also limited by the erodibility of the substrate. Fox and Bryan (1999) found that the interrill process is detachment-limited, since soil losses are decreasing after having obtained an initial peak even though the runoff rate and subsequently its transport capacity is increasing. The factors controlling the detachment processes are the shear forces induced by the surface runoff and the raindrop impact, and the reciprocal shear forces due to the cohesion of the soil particles and gravity. Given the fundamental principle that rainfall erosion occurs when the acting forces (raindrop impact and runoff) exceed the cohesion of the soil particles and the fact that different soil types erode at different rates, many authors searched for threshold driven detachment and transport equations. The most determining parameters in the equations are: the critical momentum flux (Schmidt, 1992), the mean runoff velocity, the unit stream power (Morgan et al., 1998 ; De Roo et al., 1996; McIsaac et al.,1992 or the critical shear strength (Nearing et al., 1997; Prosser and Dietrich, 1995). However, the parameters as critical momentum flux and critical shear strength are difficult to measure (Schramm and Prinz, 1993) and good relationships with the measured soil physical properties are lacking. This imposes problems when applying those detachment and transport equations in erosion modeling studies on a regional scale. Even though most velocity measurements are effectuated using the same coloured dye method, large variations are observed in the conversion factors used. Values from 0.7 and 0.8 (Zhang et al., 2003) to 0.36 (Fox and Bryan, 1999) have been used in literature and as such this factor is not standardized and comparisons cannot be made easily. Fox and Bryan (1999) also indicated that the Manning equation is not suitable to calculate the velocity of overland flow during the interrill erosion process. Therefore it is better to apply relationships using the discharge instead of the velocity parameter. Since discharges are easily measured at stream outlets, this parameter can also be used to perform inverse modeling and calibration, increasing the accuracy of the erosion model equipped with such equations.

For the erosion process in rills and gullies, Nearing et al. (1997) reported a simple but very accurate transport function using the stream power (ω) concept

$$\omega = \rho\, g\, S\, q \qquad [1]$$

Where ρ is the density of the water (g cm^{-3}), g the gravitational constant (cm s^{-2}), S the slope (m m^{-1}) and q the discharge per unit width (cm^2 s^{-1}).

Based on laboratory V-shaped flume experiments, using silt loam and sandy loam soils, these researchers found a single logistic relationship between the unit sediment load (q_s) and the stream power of the overland flow.

$$\log_{10}(q_s) = a + b\frac{e^{c+d\log_{10}(\omega)}}{1+e^{c+d\log_{10}(\omega)}} \qquad [2]$$

with a=-34.47, b=38.61, c=0.845 and d=0.412

This kind of relationship between the unit sediment load and stream power was also found by Elliot and Laflen (1993).

In our study a sediment transport model is developed based on small scale laboratory rainfall simulations for the sheet erosion process in which the sediment is delivered towards a rilling system in an agricultural field. The objective of this study is therefore to find a relationship between runoff discharge and sediment concentration under interrill conditions.

2. Materials and methods

Since the early 1970's laboratory rainfall simulations were carried out at the International Center for Eremology, Department of Soil Management, Ghent University, Belgium, to assess the parameter values of the USLE (Wischmeier and Smith, 1978) topographic factor, the soil erodibility and to evaluate the effect of chemical soil conditioners on aggregate stability and on soil susceptibility to runoff and erosion. This resulted in 133 experiments carried out between 1973 and 1998 by Pauwels (1973), Gabriels (1974), Verdegem (1979), De Beus (1983), Goossens (1987) and Gabriels et al. (1998). All these experiments were done on sandy, loamy and silty soils, mainly of loess origin. Biesemans (2000) carried out 7 additional rainfall simulator experiments on an alluvial clay soil (42% clay).

All laboratory experiments were performed on a smoothed (aggregate fractioned) soil surface to avoid possible rill formation and to ensure a broad sheet flow during the simulated rain. The intensities of the simulated rain was held constant during the experiments and ranged from 20 to 128 mm h^{-1}. The width of the soil pan was 20 to 30 cm and the length was 30 to 90 cm. The slope of the soil pan was set between 4 and 33%. The experiments lasted between 60 and 120 minutes, and the discharge Q together with the soil loss Qs was measured at 5 to 10 minutes intervals, depending on the intensity of the simulated rain. Because during the rain simulations a broad sheet flow is formed; the width of the flow equals the sample width and the volumetric water flux q per unit of surface width could be derived directly. This resulted in 672 observations of discharge (runoff) and soil loss (in the runoff water).

3. Results and discussion

The laboratory experiments resulted in unit discharges in the range 0.01 to 0.27 cm^2 s^{-1}. It was found that the stream power ω (kg s^{-3}) was the best predictor of the unit sediment load q_s (kg s^{-1} m^{-1}).

If the measured unit sediment load q_s is log-log plotted against the stream power ω of the overland flow, a linear relationship can be identified in the data. A power function fitted the data best (Equation 3).

$$q_s = 0.00015\ \omega^{1.33} \qquad r^2 = 0.86 \qquad [3]$$

It can be seen that the unit sediment load is between 1 and 3 log cycles higher for the laboratory rainfall experiments than for the flume experiments of Nearing et al. (1997).

Many other authors have posted that stream power (g s^{-3}) is the best predictor for soil detachment (D_c) and transport in either rills or by shallow flow. And hence the power function $D_c = a\omega^b$ is most commonly applied.

Zhang et al. (2002) found values of 4.29 10^{-2} for a and 1.62 for b as parameters for the power function between stream power and soil detachment by shallow flow. The set-up consisted of flume experiments with disturbed soil samples from a silt loam soil. A Pearson correlation coefficient (r^2) of 0.89 was observed.

This kind of relationship between stream power and the unit sediment load was also found by Zhang et al. (2003) using an identical set-up with undisturbed soil samples. The reported parameter values are 8.8 10^{-3} for a and 1.07 for b, with $r^2 = 0.95$, indicating that undisturbed soil is much more resistant to soil erosion than would be assumed using disturbed soil samples. Nevertheless, Schiettecatte et al. (2006) observed similar erosion rates during high intensity laboratory rainfall simulations using disturbed and undisturbed samples at the same time. This can be explained by the effect of the raindrop impact influencing both the detachment and the sediment transport process during interrill erosion (Guy et al., 1992). Because sheet flow is broader (widespread) and more shallow than rill flow, the momentum of a raindrop impact can act directly upon the soil surface. Consequently, the raindrop impact can be considered as the most important soil detachment process in interrill areas. The rain drop impact is also responsible for the increase of sediment transport capacity, due to an increased turbulence.

The relationship between the unit sediment load and the stream power is also function of the clay content (Fig. 1). The higher the clay content, the lower the unit sediment load. The parameters of the regression power equations, with the corresponding correlation coefficient are given in Table 1.

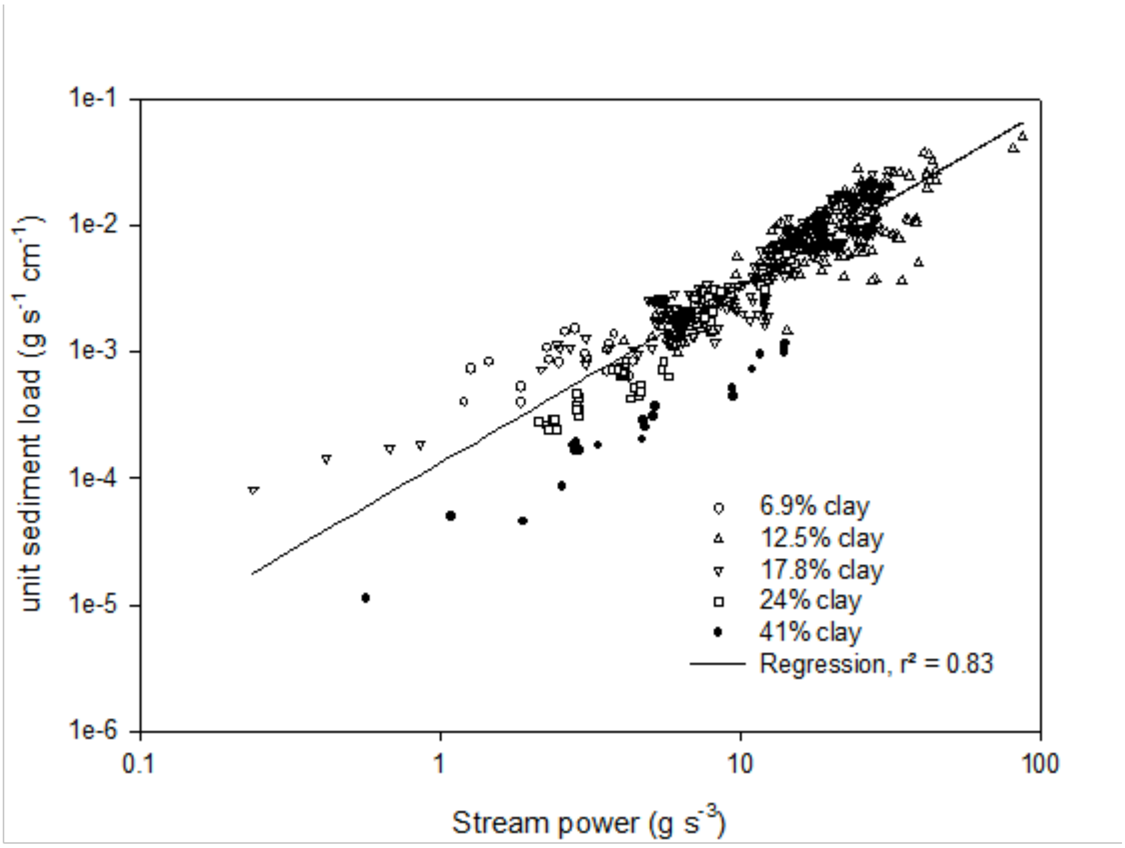

Figure 1. Relationship between stream power (g s^{-3}) and unit sediment load (g s^{-1} cm^{-1}) for soils with different clay content.

Table 1 - Parameters of power functions between stream power (g s^{-3}) and unit sediment load (g s^{-1} cm^{-1}) for laboratory rainfall simulations

% clay	**a (10^{-4})**	**b**	**r^2**
6.9	2.61	1.30	0.49
12.5	1.64	1.29	0.89
17.9	2.06	1.28	0.87
24.0	6.03	1.70	0.97
41.0	3.30	1.31	0.98

Remark that the exponents b of the regression equations are all (except one) around 1.3. The intercept of the regression equations is a measure of the erodibility of the soil. In general, the higher the clay content, the higher the cohesion and the lower the erodibility. In comparison with the values reported by Zhang et al. (2002, 2003), even lower intercepts are found.

Without the data set for the soil with 24% clay, the overall correlation increases significantly.

$$q_s = 0.000018\ \omega^{1.29} \qquad r^2 = 0.89 \qquad [6]$$

This relationship can be used to describe the erosion process in interrill areas.

4. References

Biesemans J. 2000. Erosion modeling as support for land management in the loess belt of Flanders, Belgium. Ph.D. Thesis, Ghent University, Belgium.

De Beus P. 1983. Aggregate distribution in the runoff water as a function of slope length (in Dutch), M.Sc. Thesis, Ghent University, Belgium.

De Roo APJ, Wesseling CG, Ritsema CJ. 1996. LISEM: a single-event physically based hydrological and soil erosion model for drainage basins. 1. Theory, input and output. *Hydrological Processes* **10**: 1107-1117.

Elliot WJ, Laflen J. 1993. A process-based rill erosion model. *Transactions of the ASAE* **36:** 65-72.

Fox DM, Bryan RB. 2000. The relationship of soil loss by interrill erosion to slope gradient. *Catena* **38**: 211-222.

Gabriels D. 1974. Study of the water erosion process by means of rainfall simulation on natural and artificially structured soil samples (in Dutch), Ph.D. Thesis, Ghent University, Belgium.

Gabriels D, Tack K, Cornelis WM, Erpul G, Norton D, Biesemans J. 1998. Effect of wind-driven rain on splash detachment and transport of a silt loam soil: a short slope wind-tunnel experiment. in: Proceedings of the International Workshop on technical aspects and use of wind tunnels for wind erosion control. Combined effect of wind and water on erosion processes. International Center for Eremology, Ghent University, pp. 87-93.

Goossens M. 1987. Splash erosion as a factor in the evaluation of soil erodibility (in Dutch), M.Sc. thesis, Ghent University, Belgium.

Guy BT, Dickinson WT, Rudra RP. 1992. Evaluation of fluvial sediment transport equations for overland flow. *Transactions of the ASAE* 35: 545-555.

McIsaac GF, Mitchell JK, Hummel JW, Elliot WJ. 1992. An evaluation of unit stream power theory for estimating soil detachment and sediment discharge from tilled soils. *Transactions of the ASAE* **35:** 535-544.

Morgan RPC, Quinton JN, Smith RE, Govers G. Poesen JWA, Auerswald K, Chisci G, Torri D, Styczen ME 1998. The European soil erosion model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms* **23:** 527-544

Nearing MA, Norton LD, Bulgakov DA, Larionov GA, West LT, Dontsova KM. 1997. Hydraulics and erosion in eroding rills. *Water Resources Research* **33(4):** 865-876.

Pauwels JM. 1973. Contribution to the study of water erosion by means of rainfall simulation (in Dutch), M.Sc. Thesis, Ghent University, Belgium.

Prosser IP, Dietrich WE. 1995. Field experiments on erosion by overland flow and their implication for a digital terrain model of channel initiation. *Water Resources Research* **31(11):** 2867-2876.

Schiettecatte W. 2006. Assessment of sediment and phosphorus transport from laboratory to watershed scale. PhD Thesis, Ghent University, Ghent, Belgium.

Schmidt J. 1992. Modeling long-term soil loss and landform change. In: Parsons AJ, Abrahams AD (Eds.), Overland flow, hydraulics and erosion mechanics, UCL Press, University College London. pp 409-433.

Schramm M, Prinz D. 1993. Rainfall simulation tests for parameter determination of a soil erosion model. In: Wicherek S (Ed.), Farmland erosion in temperate plains environment and hills, Elsevier, Amsterdam. pp. 373-387.

Verdegem P. 1979. Effect of slope length on the aggregate size distribution in the runoff water (in Dutch), M.Sc. Thesis, Ghent University, Belgium.

Wischmeier WH, Smith DD. 1978. Predicting rainfall erosion losses – A guide to conservation planning, USDA, Washington DC. (Agricultural Handbook 537).

Zhang GH, Liu BY, Nearing MA, Hunag CH, Zhang KL 2002. Soil detachment by shallow flow. *Transactions of the ASAE* **45:** 351-357

Zhang GH, Liu BY, Liu GB, He XW, Nearing MA 2003: Detachment of undisturbed soil by shallow flow. *Soil Science Society of America Journal* **67:** 713-719.