Impact of soil aggregates on the size selectivity of the sediment deposition process

L. BEUSELINCK, G. GOVERS*, A. STEEGEN & J. POESEN*

Laboratory for Experimental Geomorphology, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, Belgium

e-mail: laurent.beuselinck@geo.kuleuven.ac.be

Abstract Experiments were conducted to evaluate the impact of sediment concentration, slope and discharge on sediment deposition rates, patterns and sediment sorting using well-aggregated sediment. Comparison of data from aggregated sediment with experimental data obtained using completely dispersed sediment shows that the aggregated sediment has an important influence on both sediment delivery ratio and deposition pattern. Large aggregates of low density are easily transported by rolling over the bed of the flume. These aggregates have a dispersed size distribution closely resembling the source soil material. This results in limited sediment sorting during transport over an area of net deposition. Furthermore, considerable quantities of organic matter, incorporated within soil aggregates, are deposited. Therefore, one may conclude that soil aggregates have an important impact on the transport of nutrients and contaminants by overland flow.

INTRODUCTION

Sediment deposition by overland flow is a highly size-selective process, in which mainly coarse sediment is deposited (Beuselinck *et al.*, 1999c). As a result, the relative importance of the finer fractions in the flow increases when sediment is transported over an area of net deposition. This has important consequences for the off-site effects of soil erosion, since sediment associated nutrients and contaminants are preferentially bound to the finest sediment fractions (Horowitz, 1991).

Several studies have shown that, in certain circumstances, sediment is transported in aggregated form rather than as primary particles (e.g. Young, 1980; Walling & Moorehead, 1989; Slattery & Burt, 1997). Field surveys showed that, during intense rainfall events in summer, significant amounts of fine sediment, incorporated in soil-aggregates, are deposited (Beuselinck *et al.*, 2000). Consequently, the size selectivity of the deposition process in these circumstances is compensated for by the presence of soil aggregates in the deposits.

Therefore, the aim of this paper is to evaluate the impact of soil aggregates on the size selectivity of the deposition process. Flume experiments were conducted to evaluate the impact of sediment concentration, slope and discharge on sediment deposition rates, patterns and sediment sorting in the presence of soil aggregates. These experimental results are compared to those on sediment deposition obtained using totally dispersed sediment (Beuselinck *et al.*, 1999b,c).

* *Funded by:* Fund for Scientific Research Flanders.

EXPERIMENTAL SETUP

In the experiments deposition in a flume was studied. Clear water was introduced at the top end of a lead-in flume. Soil aggregates were introduced into the water at the top of the lead-in flume using an overhead sediment hopper. A conveyer belt supplied sediment at a constant, predetermined rate. By adjusting the rate of sediment inflow to the water flow rate, specific sediment concentrations were obtained. The lead-in flume was connected to a 2.6 m long and 0.117 m wide experimental flume at its lower edge.

Sediment was prepared by using a well-aggregated silty soil from which the stones were removed by passing it through a 5 mm screen. The sieved soil was air-dried before introducing it into the sediment hopper. The dispersed and undispersed grain-size distributions of the silty soil used in these experiments are given in Table 1. The silty soil has an organic matter content of approximately 1%.

Table 1 Dispersed and undispersed size distribution of the aggregated inflow sediment.

	<2 μm	2–4 μm	4–8 μm	8–16 μm	16–32 μm	32–63 μm	>63 μm
Dispersed (%)	12.2	3.4	4.1	9.3	28.9	34.6	7.5
Undispersed (%)	2.0	0.6	1.3	5.1	26.0	43.2	21.8

In total 22 experiments were conducted. Each experiment was carried out using a constant discharge and a constant inflow sediment concentration. Flow rates ranged from 0.0004 to 0.0019 m^2 s^{-1} and sediment concentrations ranged from 48 to 103 kg m^{-3}. For the depositional flume, slopes of 1, 2 and 4% were used.

Sediment samples were collected at the end of the flume. These were subsequently used to assess the sediment concentration by oven drying. Samples of the inflow, outflow and deposited sediments were analysed for their dispersed and undispersed (or aggregated) size distribution. Size analyses were completed by laser diffractometry (Coulter LS-100) and converted to sieve-pipette data (Beuselinck *et al.*, 1998, 1999a). By comparing the inflow and the outflow sediment concentrations for each size class, sediment delivery ratios (SDR) could be determined. The organic matter content of the inflow, the deposited and the outflow sediments were determined by the method of Walkley & Black (1934).

RESULTS

The overall sediment delivery ratio (SDR)

Figure 1 shows the overall SDR *vs* unit discharge for all experiments conducted with well-aggregated sediment. The SDR increases gradually with increasing unit discharge. The increase in SDR with increasing discharge is less pronounced at higher discharges. The SDR increases much more rapidly at a 4% slope than at a 1% slope. Consequently, the overall SDR increases strongly with increasing flume bed steepness for experiments conducted at similar flow rates.

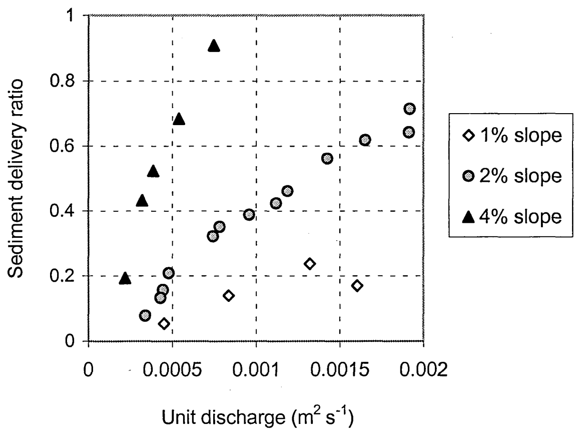

Fig. 1 Sediment delivery ratio *vs* unit discharge for experiments conducted with well-aggregated sediment on 1, 2 and 4% slopes.

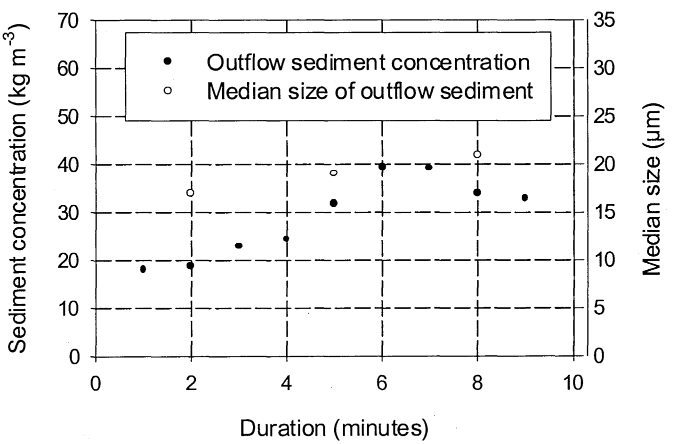

Fig. 2 Outflow sediment concentration and median (after dispersion) of the exported sediment for an experiment conducted with well-aggregated sediment on a 2% slope.

Although the flow rate and the inflow sediment concentration stay constant, there is a strong variation in outflow sediment concentration during the experimental run (Fig. 2). Outflow sediment concentration increases with time. For some experiments, outflow sediment concentration subsequently decreases by the end of the experimental run. Variations in median size of the outflow sediment *vs* time are less pronounced (Fig. 2).

Sediment-size distribution

Analysis of the dispersed grain-size data shows that finer sediment is more easily transported over a depositional area than coarser sediment (Fig. 3). Nevertheless, there is a limited difference between the SDR of the finer and the coarser fractions

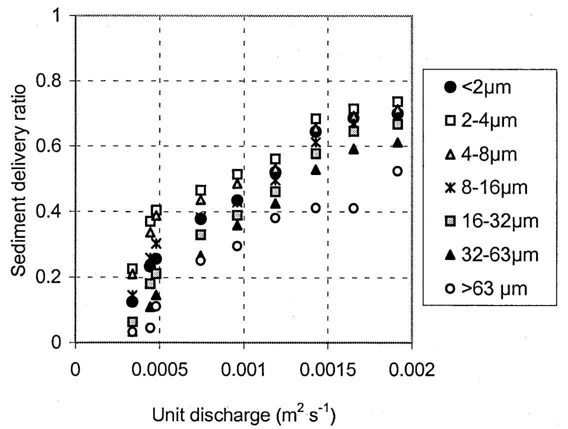

Fig. 3 Sediment delivery ratio *vs* unit discharge for each of the seven size classes (dispersed grain-size data) for experiments conducted with well-aggregated sediment on a 2% slope.

within each experiment. This indicates that sediment transport over an area of net deposition is only slightly size-selective when the sediment is mainly transported as aggregates. The experimental results also show that the dispersed size distribution of the deposited sediment is very similar to the dispersed size distribution of the inflow sediment. Furthermore, all size fractions react in the same way with an increase in flow rate. For all size fractions, a gradual increase with increasing discharge can be observed (Fig. 3). The SDRs for the fractions 2–4 µm and 4–8 µm are always slightly higher than those for the clay fraction (<2 µm).

Figure 4 shows that there is an almost perfect agreement between the SDR of the clay fraction and the organic matter delivery ratio. The strong relationship between

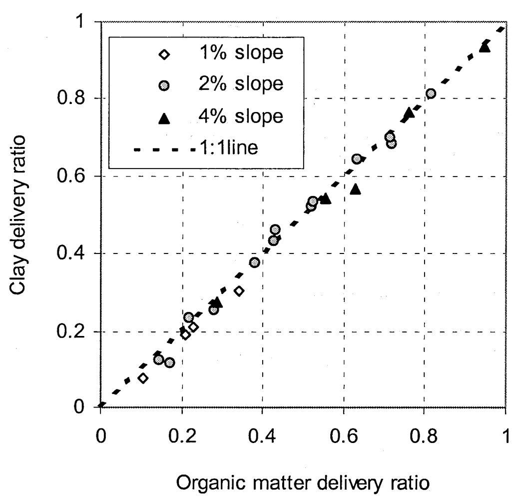

Fig. 4 Sediment delivery ratio of the clay fraction (dispersed grain-size data) *vs* the organic matter delivery ratio for the experiments conducted with well-aggregated sediment.

clay and organic matter can be attributed to the formation of relatively stable organo-mineral/colloidal complexes (Sutherland, 1999).

DISCUSSION

Beuselinck *et al.* (1999b,c) presented results of similar experiments on sediment deposition conducted using totally dispersed silty sediment. Comparison of the experimental data obtained in both the presence and absence of well-aggregated material in the inflow sediment shows that the presence of soil aggregates strongly affects the deposition process (Fig. 1 *vs* Fig. 5). The presence of aggregates in the inflow sediment results in a different relationship between the SDR and unit discharge. In the experiments conducted with completely dispersed sediment, a sudden change in relationship between the SDR and unit discharge was observed at 2% and 4% slopes, which can be related to a critical shear stress value (Beuselinck *et al.*, 1999c). However, in the experiments conducted with well-aggregated sediment, the SDR increases gradually with increasing unit discharge for the three slopes investigated. Moreover, even at low flow rates, slope steepness affects the SDR if well-aggregated material is used, whereas it only has a limited influence on the SDR at low flow rates in the experiments carried out with completely dispersed sediment.

In the experiments presented in this paper, air-dried well-aggregated sediment was brought into clear water. As soil aggregates are very sensitive to rapid wetting, considerable amounts of aggregates broke down by slaking into water-stable (micro-)aggregates and/or primary particles (Le Bissonnais, 1996). Nevertheless, comparison of the dispersed and undispersed size distributions confirms that aggregates are present in the exported sediment (Fig. 6). This indicates that at least part of the inflow sediment is transported and deposited in aggregated form.

The median size of aggregated sediment is significantly higher than the median size of the primary particles. However, soil aggregates have a lower density than primary particles (Young, 1980). Consequently, soil aggregates are more easily

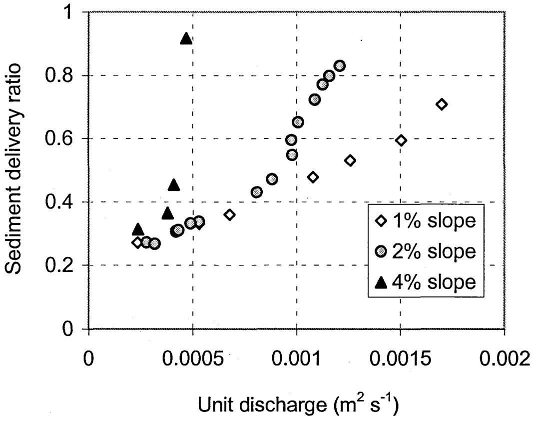

Fig. 5 Sediment delivery ratio *vs* unit discharge for experiments conducted with completely dispersed sediment on 1, 2 and 4% slopes (Beuselinck *et al.*, 1999c).

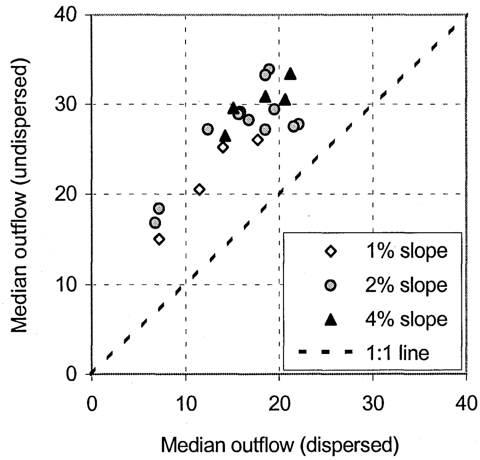

Fig. 6 Median size of the undispersed outflow sediment *vs* the median size of the dispersed outflow sediment for experiments conducted with well-aggregated sediment.

transported than primary particles of an equivalent size. Davis *et al.* (1983) showed experimentally that particle density has a greater impact on sediment transport and deposition by overland flow than does particle size. Furthermore, aggregates usually have a more rounded shape and are therefore more prone to rolling over the flume bed than primary particles of the same size (Lu *et al.*, 1988). Rolling of aggregates on the flume bed was clearly observed during the experiments.

Bedload transport of relatively large aggregates with a low particulate density partly explains the observed relationship between the SDR and unit discharge. As bedload transport increases with slope steepness (Graf, 1971), the observed relationship between the SDR and slope steepness can be explained. In the experiments conducted with well-aggregated sediment, bedload transport is thus a dominant transport mode. However, in the experiments conducted with totally dispersed sediment, only limited amounts of coarse sediment were transported by rolling over the bed of the flume, whereas most sediment was transported as suspended load (Beuselinck *et al.*, 1999c).

The observed variation in outflow sediment concentration with time (Fig. 2) can also be explained by the occurrence of bedload transport. During the experiment, sediment accumulated on the bottom of the flume creating a steeper bedslope. This produced increased bed load transport, since bedload transport is sensitive to changes in bed slope. The increased bedload transport caused a decrease in sediment deposition on the bed and therefore the sediment yield at the flume outlet increased. This contrasts with the experiments in the absence of soil aggregates, where the outflow sediment concentration stays more or less constant with time, since bedload transport is less pronounced in these experiments (Beuselinck *et al.*, 1999b).

Analysis of the experimental data obtained from totally dispersed sediment clearly shows the existence of a threshold value at which there is a sharp rise in transport capacity (Beuselinck *et al.*, 1999c). Below this threshold value, sediment deposition can be predicted by a simple settling theory, whereas above the threshold value, a transport term needs to be incorporated. At these flow conditions re-entrainment of previously deposited material occurs (Beuselinck *et al.*, 1999b). Einstein (1950) also assumed that there was an exchange between non-cohesive bed material and transported sediment in rivers. In contrast, Lu *et al.* (1989) assumed that no exchange of particles took place between the sediment in the flow and the previously deposited sediment in their deposition experiments with an aggregated silt loam soil, which they defined as a cohesive sediment. They referred to work on cohesive sediment settling by Partheniades (1971). Several authors indeed showed that re-entrainment does not occur during cohesive sediment settling (Partheniades, 1971; Lau & Krishnappan, 1994). Furthermore, Mitchener & Torfs (1996) showed that the erosion resistance of mud/sand mixtures increases with increasing content of fines. They found a critical content of fines between 10 and 20%. Below this critical content, the mixture can be treated as a cohesionless sediment; above this limit, cohesive forces determine the behaviour of the mixture. In our experiments the deposited sediment consisted, on average, of *c.* 12% clay. Thus, the higher resistance of the deposited sediment to flow re-entrainment could explain the absence of a change in relationship between the SDR and unit discharge for the experiments conducted with aggregated sediment. Nevertheless, the experimental results show that most clay is deposited in aggregated form. Further research has to show if this clay can be responsible for an increase in resistance to re-entrainment.

The experimental data obtained using totally dispersed sediment (Beuselinck *et al.*, 1999b,c) clearly showed that sediment deposition is a highly size-selective process (Fig. 7). Small particles are easily exported out of the flume, whereas coarse particles, up to a threshold value, are almost totally deposited. Once the threshold value is exceeded, the export of coarse sediment increases sharply. On the other hand, the export of intermediate-sized particles increases almost linearly with increasing discharge. If the behaviour of these size classes is compared with the results obtained from experiments conducted with well-aggregated inflow sediment (Fig. 3), one can conclude that the size selectivity is much less pronounced here.

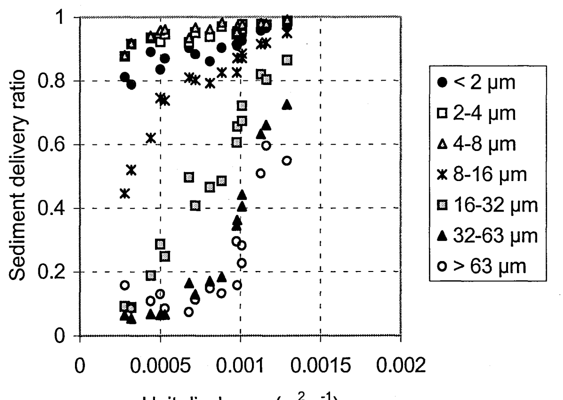

Fig. 7 Sediment delivery ratio *vs* unit discharge for each of the seven size classes for experiments conducted with completely dispersed sediment on a 2% slope (Beuselinck *et al.*, 1999b).

That is, the SDR of each size fraction increases gradually with increasing unit discharge. Because all grain-size classes react in the same way to changes in flow conditions, sediment transport and deposition must mainly occur in aggregated form.

IMPLICATIONS FOR NUTRIENT AND CONTAMINANT TRANSPORT

Because silty soil aggregates often have a dispersed size distribution similar to that of the source soil (Beuselinck *et al.*, 2000), considerable amounts of fines and their associated pollutants are transported within larger aggregates. When sediment deposition occurs in aggregated form the size selectivity of the deposition process is partially offset by the presence of soil aggregates in the deposits. Furthermore, considerable quantities of organic matter, incorporated within soil aggregates, are deposited. Thus, sediment size characteristics play an important role in the pollution potential of eroded sediment and consequently have to be taken into account when modelling the sediment deposition process. Ignoring the aggregate size distribution of eroded sediment results in a strong overestimation of the export of fines and sediment-associated pollutants.

These experimental data confirm that the potential contrast between dispersed and undispersed size distribution of the eroded sediment has to be taken into account to understand the size selectivity of the sediment deposition process. Furthermore, in order to assess the off-site effect of soil erosion, information on the size distribution of resulting fragments after aggregate break-down is necessary (Le Bissonnais, 1996). Taking into account the processes related with aggregated sediment transport introduces additional complexity to the modelling of sediment transport over an area of net deposition. Aggregate stability, aggregate transportability, impact of aggregates on flow re-entrainment and the sensitivity of aggregates to transport by rolling over the bed, all influence the deposition process. The magnitude of these processes strongly affects not only the total sediment delivery but also the pollution potential of eroded sediment reaching a river system. Therefore, the next challenge in modelling sediment transport by overland flow over an area of net deposition is the accurate prediction of the impact of soil aggregates on the deposition process.

Acknowledgements This research was conducted as part of a research project funded by the Katholieke Universiteit Leuven (OT 95/15) and the Fund for Scientific Research (G0251-96). Thanks are also due to J. Meersman for his assistance during the construction of the experimental setup.

REFERENCES

Beuselinck, L., Govers, G., Poesen, J., Degraer, G. & Froyen, L. (1998) Grain-size analysis by laser diffractometry: comparison with the sieve-pipette method. *Catena* **32**, 193–208.

Beuselinck, L., Govers, G. & Poesen, J. (1999a) Assessment of micro-aggregation using laser diffractometry. *Earth Surf. Processes and Landforms* **24**(11), 41–49.

Beuselinck, L., Govers, G., Steegen, A., Hairsine, P. B. & Poesen, J. (1999b) Evaluation of the simple settling theory for predicting sediment deposition by overland flow. *Earth Surf. Processes and Landforms* **24**(11), 993–1007.

Beuselinck, L., Govers, G., Steegen, A. & Quine, T. A. (1999c) Sediment transport by overland flow over an area of net deposition. *Hydrol. Processes* **13**(17), 2769–2782.

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I. & Poesen, J. (2000) Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. *Geomorphol.* **32**(1–2), 69–82.

Davis, S. S., Foster, G. R. & Huggins, L. F. (1983) Deposition of non-uniform sediment on concave slopes. *Trans. Am. Soc. Agric. Engrs* **23**, 1057–1063.

Einstein, H. A. (1950) The bed-load function for sediment transportation in open channel flows. *Tech. Bull. no. 1026, US Dept of Agriculture, Soil Conservation Service, Washington DC, USA.*

Graf, W. H. (1971) *Hydraulics of Sediment Transport*. McGraw-Hill, New York, USA.

Horowitz, A. J. (1991) *A Primer on Sediment-Trace Element Chemistry*, second edn. Lewis Publishers, Chelsea, Michigan, USA.

Lau, Y. L. & Krishnappan, B. G. (1994) Does re-entrainment occur during cohesive sediment settling? *J. Hydraul. Engng, ASCE* **120**(2), 236–244.

Le Bissonnais, Y. (1996) Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* **47**, 425–437.

Lu, J. Y., Cassol, A., Foster, G. R. & Neibling, W. H. (1988) Selective transport and deposition of sediment particles in shallow flow. *Trans. Am. Soc. Agric. Engrs* **31**(4),1141–1147.

Lu, J. Y., Cassol, E. A. & Moldenhauer, W. C. (1989) Sediment transport relationship for sand and silt loam soils. *Trans. Am. Soc. Agric. Engrs* **32**(6), 1923–1931.

Mitchener, H. & Torfs, H. (1996) Erosion of mud/sand mixtures. *Coastal Engng* **29**(1–2), 1–25.

Partheniades, E. (1971) Erosion and deposition of cohesive materials. In: *River Mechanics* (ed. by H. W. Shen), 1–91. Water Resources Publications, Fort Collins, Colorado, USA.

Slattery, M. C. & Burt, T. P. (1997) Particle size characteristics of suspended sediment in hillslope runoff and stream flow. *Earth Surf. Processes and Landforms* **22**, 705–719.

Sutherland, R. (1999) Distribution of organic carbon in bed sediments of Manoa stream, Oahu, Hawaii. *Earth Surf. Processes and Landforms* **24**, 571–583.

Walling, D. E. & Moorehead, P. W. (1989) The particle size characteristics of fluvial suspended sediment: an overview. *Hydrobiologia* **176/177**, 125–149.

Walkley, A. & Black, I. A. (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **37**, 29–38.

Young, R. A. (1980) Characteristics of eroded sediment. *Trans. Am. Soc. Agric. Engrs* **23**, 1139–1142, 1146.