PARTICLE SIZE SELECTIVITY CONSIDERATIONS IN SUSPENDED SEDIMENT BUDGET INVESTIGATIONS

P.M. STONE and D.E. WALLING

Department of Geography, University of Exeter, Exeter EX4 6QX, England.

Abstract. The delivery of suspended sediment from drainage basins has frequently been quantified in mass terms by use of the sediment budget approach, which identifies sources, storage and output of mobilised sediment. An attempt is presented here to define the main components of a generalised suspended sediment budget for a drainage basin in Devon, U.K. in terms of particle size characteristics and grain size selectivity, rather than total amounts of sediment. Samples of sediment mobilised from the hillslopes, fluvial suspended sediment and suspended sediment deposited on the river bed were all collected for particle size characterisation. These samples were then treated to remove organic matter and their chemically dispersed (absolute) particle size composition was measured using a Coulter LS130 laser granulometer. Where possible, measurements of the natural *in-situ* particle size distribution (effective particle size) were also undertaken. Samples were collected at different times of the year so that temporal variation of hydrometeorolgical and ground conditions was represented. Comparison of the results for the different components of the delivery process shows that significant particle size selectivity occurs in the mobilisation and transfer of sediment from the hillslopes to the basin outlet. This reflects the particle size selectivity of detachment, transport and deposition processes, which is in turn influenced by the aggregation or flocculation (effective particle size) of the sediment.

KEYWORDS: suspended sediment delivery, particle size selectivity, mobilised sediment, fine-grained bed sediment

1. Introduction

Suspended sediment budget studies have quantified sources and sinks in the suspended sediment delivery system and the fluxes involved (e.g. Walling, 1988; Sutherland and Bryan, 1991) but there have been very few attempts to express the suspended sediment budget in terms of the particle size composition or particle size selectivity involved. Particle size selectivity occurs if a sediment sample is enriched or depleted in certain particle sizes when compared to its source, due to the erosion, transportation or deposition processes operating. Existing investigations of particle size selectivity have considered sediment mobilisation from hillsplopes (e.g. Parsons *et al.* 1991), transport of suspended sediment in rivers (e.g. Walling and Moorehead, 1987), deposition of suspended sediment on the river bed (e.g. Tipping *et al.*, 1993; Droppo and Stone, 1994) or overbank suspended sediment depositions (e.g. Lambert and Walling, 1987). Most concentrate on individual components of the sediment budget and few consider the particle size selectivity of sediment delivery (e.g. Sutherland and Bryan, 1989). The aim of this paper is quantify the sediment budget of a river in terms of its particle size characteristics and particle size selectivity occurring during sediment delivery.

2. Study Area and Methods

The 46km^2 drainage basin of the River Dart, a tributary of the River Exe, Devon, U.K. was chosen for the study. The underlying geology is Upper Carboniferous Culm Measures (sandstones interbedded with shales, mudstones and siltstones) and the land use as classified by the Ministry of Agriculture, Fisheries and Food (MAFF) 1994 statistics comprises 10.8% cultivated, 82.2% grassland and 7% woodland. The topography is characterised by well developed interfluves and incised valleys (average slope angle 11°). Mean annual precipitation is almost 900mm, with 60% falling during the winter season. Existing suspended sediment tracing studies suggest that over the longer-term ca. 79% of the sediment yield is derived from surface sources and ca. 21% from channel banks (Walling *et. al.* 1993). Pasture areas, frequently poached by livestock in winter, represent the dominant sediment source. The specific suspended sediment yield from the basin has been estimated to be ca. 58 t $km^{-2}year^{-1}$ (Walling and Webb, 1987). The main components of the suspended sediment budget were identified as sediment mobilisation from the basin hillslopes, transport of suspended sediment by the river and the deposition of suspended sediment on the bed of the river. The particle size characteristics and selectivity of these three main components were investigated.

A field portable rainfall simulator based on the design of Bowyer-Bower and Burt (1989) was used to generate rainfall of 7 mm/hour intensity for 3 hours. This design storm was representative of natural conditions that caused significant suspended sediment transport in the river throughout the year. Sediment samples from pasture land (the dominant source of suspended sediment) were collected at the base of the simulator plots. Seasonal variation in sediment mobilisation was investigated on a monthly basis using plots with similar slope and land use at Well Farm. Single simulation runs on similar plots at other locations in the basin indicated that the results from Well Farm were representative of sediment mobilisation from pasture throughout the basin. Samples of the top 1 cm of soil adjacent to the plots were compared with the samples of mobilised sediment to determine whether particle size selectivity was occurring.

Suspended sediment samples were collected from the river channel during natural flood events when the sediment concentration exceeded $100mgl^{-1}$. Samples were either collected manually using a USDH 48 depth integrating sampler or using automatic rising stage siphon samplers. The latter were deployed at 5 sites within the basin to determine whether spatial variation in the particle size composition of suspended sediment existed.

A sealed, removable bed trap based on the design of Phillips (1996) and containing natural bed sediment was used to collect samples of suspended sediment deposited on the river bed. The trap was initially filled with sediment < 1 mm. During flood events the seal was removed and any sediment in the trap smaller than 1 mm could be assumed to have been deposited during the event studied. After the event, the trap was removed from the river, the contents resuspended in clear water and samples collected at three stages of resuspension (stage 1 to 3) with increasing depth of agitation of the trap contents. The trap was located at the basin outlet and the spatial representativeness of the results obtained was tested by mobilising deposited sediment at five other locations throughout the basin at low flow following a flood event. An area of the bed was isolated within a steel cylinder and the surface agitated with a stick, allowing samples of resuspended sediment to be collected from the water trapped in the cylinder. These samples did not relate to a specific flood event but were not significantly different

(Mann-Whitney U test 95% confidence) from samples collected from the bed trap during the preceding flood event. No significant spatial variation in deposition was identified.

A Coulter LS 130 laser granulometer with a measurement range of 0.1 to 800μm was used to measure the particle size distribution of samples. Hydrogen peroxide was added to each sample to remove the organic fraction, and each was resuspended in sodium hexametaphosphate and ultrasonically dispersed so that a measure of the absolute particle size distribution (Ongley *et al.* 1981) could be made using the laser granulometer. Assessment of particle size selectivity associated with the various components of the suspended sediment budget was based on the absolute particle size distributions. Where possible, some suspended sediment samples and samples of mobilised sediment were not allowed to settle, but were quickly returned to the laboratory and their particle size composition measured without pre-treatment, using the laser granulometer. Such data were designated the effective particle size distribution by Ongley *et al.* (1981), and reflect the presence of composite particles (aggregates/flocs), and primary particles. Whilst not providing a true measure of the *in situ* particle size distribution, Phillips and Walling (1995) suggest that this measurement technique produces adequate results. The absolute particle size distribution of the same samples were subsequently measured after treatment for comparison. Composite particles associated with samples collected from the hillslopes are referred to as "aggregates" whilst those associated with the suspended sediment samples collected from the river are termed "flocs". Comparison of particle size distributions was based on clay (<2μm), four silt (2-5μm, 5-10μm, 10-20μm and 20-63μm) and sand (>63μm) size classes. Any enrichment or depletion in each size classes was ascribed to particle size selectivity.

3. Results and Discussion

3.1. PARTICLE SIZE SELECTIVITY OF SEDIMENT MOBILISATION FROM THE HILLSLOPES

A comparison of the average absolute particle size distribution of samples of soil and mobilised sediment collected on a monthly basis from the Well Farm site (Figure 1) indicates that there is a particle size selective mobilisation of sediment finer than 20-60μm, whilst the sand-sized material remains *in-situ*. This result is based on average values and although the soil sample did not display a significant seasonal variation (maximum standard deviation 2.24 for the 10-20μm silt class), the mobilised sediment samples showed significant seasonal variation (Figure 2). A statistically significant difference (Mann-Whitney U test 95% level of confidence) was identified between samples collected during the October-March period (autumn/winter season) and April-August period (spring/summer season). The particle size distributions of autumn/winter samples were generally finer than the spring/summer samples. During the autumn/winter, the degree of grass cover decreased and the soils became saturated. Runoff volumes were greater in the autumn/winter than spring/summer but there would appear to be an inverse relationship between flow and the size of sediment transported.

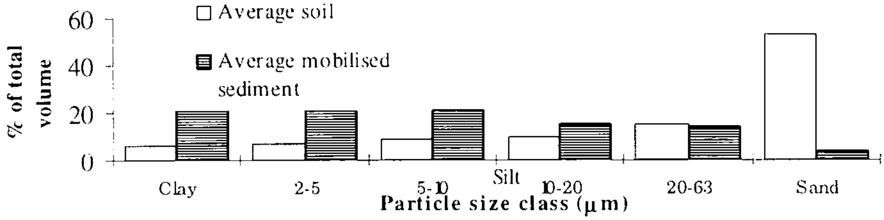

Fig. 1 The averaged absolute particle size distributions for the soil samples and for mobilised sediment in runoff collected at Well Farm on a monthly basis.

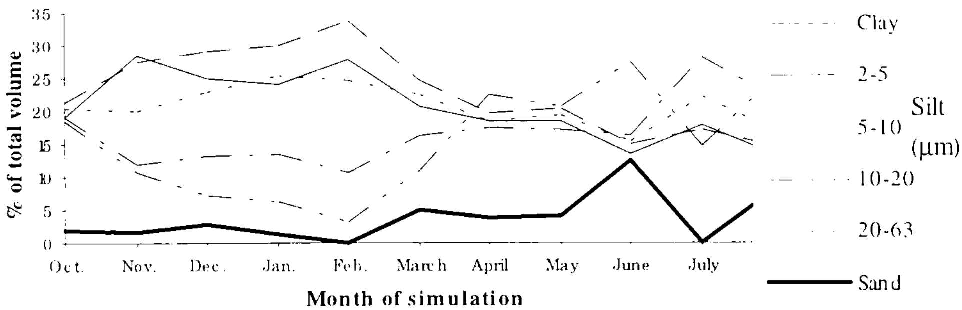

Fig. 2 The relative contribution of each of the absolute particle size classes for the samples of mobilised sediment collected during the monthly simulation runs undertaken at Well Farm.

The effective particle size distribution of samples of mobilised sediment collected from monthly simulation runs also evidenced seasonal variation. The effective and absolute particle size distributions for a sample from each season are compared in Figure 3.

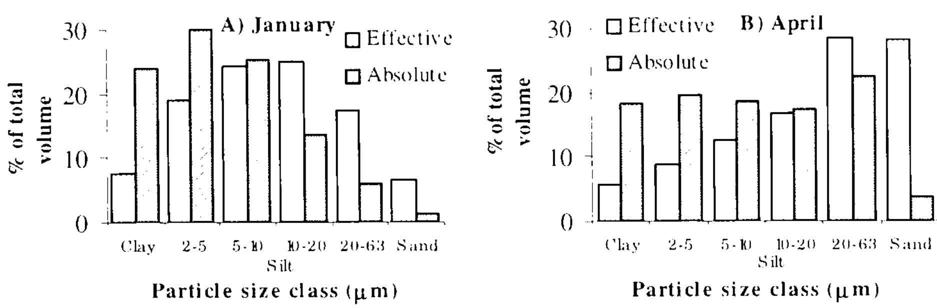

Fig. 3 A comparison of the effective and absolute particle size distributions of samples collected using the rainfall simulator in January (A) and April (B)

A comparison of the effective particle size distributions from each season shows that a greater amount of primary and aggregate particles in the 20-63μm silt and sand size classes are mobilised during the spring/summer whilst greater amounts of 2-5μm, 5-10μm and 10-20μm silt are mobilised during the autumn/winter. The aggregates associated with mobilised sediment are therefore larger in the spring/summer than in the autumn/winter. When these aggregate particles are chemically dispersed to produce the primary particle composition (absolute particle size distribution) there will be an enrichment of particles finer than the aggregates. Since the effective particle size of autumn/winter samples was finer than spring/summer the resultant absolute particle size is also finer. The seasonal difference in absolute particle size previously noted can therefore be regarded as supply-controlled.

3.2. THE PARTICLE SIZE SELECTIVITY OF SUSPENDED SEDIMENT TRANSPORT

A comparison of the absolute particle size distribution of mobilised sediment samples obtained from the monthly simulations with the average absolute particle size distribution of suspended sediment samples taken from floods at a similar time (Figure 4) suggested that in general the suspended sediment is coarser than the mobilised sediment in the autumn/winter but finer in the spring/summer. This could either be caused by seasonal variations in river flow such that increasing discharge transports increasingly larger particles or could be related to sediment supply factors. The relationship between discharge and sand sized sediment for both effective and absolute particle size distributions (Figure 5) of all suspended sediment samples

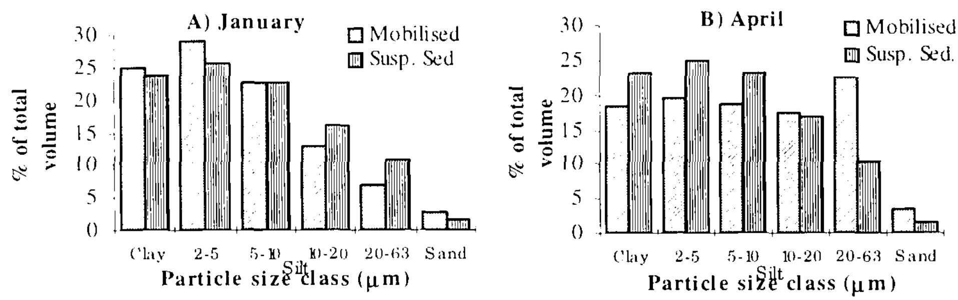

Fig. 4 A comparison of the absolute particle size composition of mobilised sediment and suspended sediment. The samples in (A) were collected during autumn/winter conditions and those for (B) during spring/summer

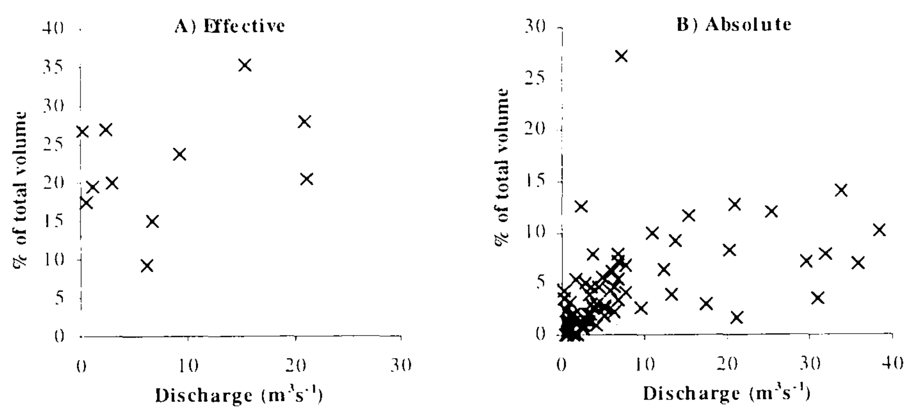

Fig. 5 The relationship between the % sand content of suspended sediment and discharge for both the effective (A) and absolute (B) particle size distributions of suspended sediment

collected evidenced little relationship. The seasonal variation noted above would therefore appear to be supply-controlled..

It is recognised that only the particle size characteristics of sediment mobilised from pasture land are considered in this study. This source was suggested by Walling *et al.* (1993) to be the main surficial source and it represented the dominant land use in the basin. Other sources of suspended sediment such as channel banks are noted but Walling *et al.* (1993) suggested that their contribution was relatively small and did not vary seasonally. Comparison of suspended sediment with sediment mobilised from intensively grazed pasture land was there felt to be valid. Figure 6 shows that, as with mobilised sediment (Figure 2), the average particle size composition of suspended sediment evidenced seasonal variation, but in this case the spring/summer samples contain greater proportions of finer sediment than those for the autumn/winter. This would be expected due to the reduced competence of runoff to transport coarser sediment

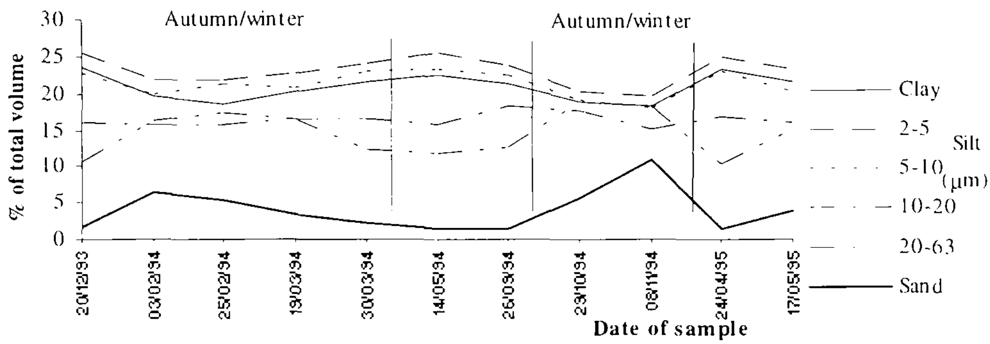

Fig. 6 Inter-storm variation in the absolute particle size composition of suspended sediment samples collected during flood events.

from the hillslopes to the channel during the spring/summer. However, when the suspended sediment and mobilised sediment are compared (Figure 3) the suspended sediment is seen to be finer than the mobilised sediment in spring/summer but coarser in autumn/winter, the latter suggesting deposition of fine sediment on the hillslopes. This may result from the deposition of large aggregate particles from the sediment transported from the hillslopes to the river channel. Figure 3 implied that autumn/winter aggregate particles were composed of finer primary particles than spring/summer aggregates Therefore, deposition of aggregates would cause a net reduction in the importance of finer sediment size classes in the absolute particle size distribution of the suspended sediment samples collected during the autumn/winter.

A comparison of representative effective particle size distributions and their equivalent absolute particle size distributions for suspended sediment collected during the autumn/winter and spring/summer seasons is shown in Figure 7. Both the autumn/winter effective and absolute particle size distributions are coarser than those for the spring/summer sample, the opposite trend to that noted for the mobilised sediment samples. This confirms that the larger aggregate particles mobilised from the hillslopes in the spring/summer did not reach the channel.

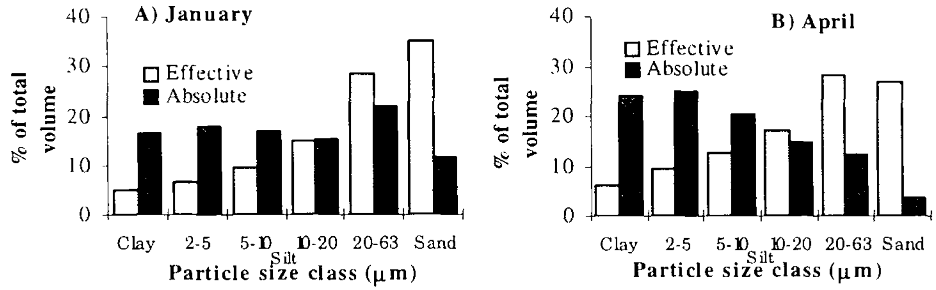

Fig. 7 A comparison of the effective and absolute particle size composition of suspended sediment. The results presented are for a sample collected in autumn/winter (A) and spring/summer (B)

3.3. THE DEPOSITION OF SUSPENDED SEDIMENT ON THE BED OF THE RIVER

A comparison of the samples of deposited suspended sediment recovered from the bed trap suggested that the degree of disturbance involved in resuspending the sediment did not influence the absolute particle size composition (Figure 8). A comparison with the absolute particle size distribution of suspended sediment also showed that coarser suspended sediment particles are selectively deposited. The finer size classes are, however, also deposited, reflecting the role of the effective particle size of the suspended sediment in the selective deposition of particles. The settling velocities of primary particles in the finest size classes are probably too low for deposition to occur, but they may be deposited as a components of flocs which have higher settling velocities than the particles of which they are composed.

Rising limb suspended sediment samples collected along the course of the river at similar times during the flood wave and samples of sediment deposited on the river bed, collected from similar locations using the cylinder showed no significant spatial variation

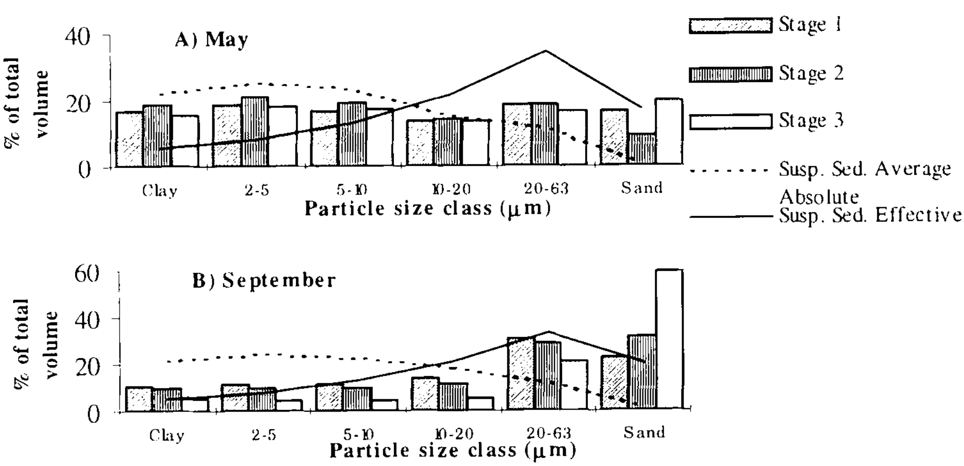

Fig. 8 The absolute particle size composition of samples collected during the three stages of resuspension of suspended sediment deposited in the bed trap during the events of 14/5/94 (A) and 26/9/94 (B). Representative effective and absolute particle size distributions for suspended sediment collected from the same event are shown.

(Mann-Whitney U test 95%). Whilst the deposition of suspended sediment onto the river bed is particle size selective, the total amounts deposited are relatively small and this appears to have no effect on the particle size composition of suspended sediment, which did not change significantly downstream.

4. Conclusion

There is clear evidence of particle size selectivity in the delivery of suspended sediment from the hillslopes to the basin outlet of the River Dart. Sediment finer than sand was preferentially mobilised from the hillslopes and most of the sand-sized sediment remained *in situ*. Both the effective and absolute particle size composition of this mobilised sediment varied seasonally. There was no clear relationship between suspended sediment particle size characteristics and river flow, suggesting that any variation observed was a result of supply factors rather than transport factors. Seasonal variation was also identified in the particle size composition of suspended sediment. A comparison of mobilised and suspended sediment suggested that particle size selectivity was occurring in the transport of sediment to the river channel, such that not all of the mobilised sediment reached the river. Some particle size classes of suspended sediment are selectively deposited in the river bed. This deposition is influenced by the effective particle size characteristics of the suspended sediment, but it appears not to have any effect on the particle size composition of the suspended sediment due to the relatively small amounts of deposition involved.

Acknowledgements

The authors gratefully acknowledge the U.K. Natural Environment Research Council in providing a Research Studentship to P.M.S. and the co-operation of landowners.

References

Bowyer-Bower, T.A.S. and Burt, T.P.: 1989, *Soil Technology*. **2** 1-16.
Droppo, I.G. and Stone, M.: 1994, *Hydrological Processes*. **8**, 101-111
Lambert, C.P. and Walling, D.E.: 1987, *Geografiska Annaler*. **69A 3-4**, 393-404.
Ongley, E.D., Bynoe, M.C. and Percival, J.B.: 1981, *Can J.Earth Sci.* **18**, 1365-1379.
Parsons, A.J., Abrahams, A.D. and Shiu-Hungluk Luk.: 1991, *Earth Surf. Proc. Landforms* **16**, 143-152.
Phillips, J.M. and Walling, D.E.: (1995), *Water Res.* **29(11)** 2498-2508.
Phillips, J.M.: 1996, *The Effective Particle Size Characteristics of Fluvial Suspended Sediment*. Unpublished Thesis, University of Exeter.
Sutherland, R.A. and Bryan, R.B.: 1989, *Catena* **16**, 189-204.
Sutherland, R.A. and Bryan, R.B.: 1991, *Earth Surf. Proc. Landforms* **16**, 383-398.
Tipping, E., Wolf, C. and Clarke, K.: 1993, *Hydrological Processes*. **7**, 263-277.
Walling, D.E.: 1988, *J. Hydrol.* **100**, 113-141.
Walling, D.E. and Moorehead, P.W.: 1989, *Hydrobiol.* **176/177**, 125-149.
Walling, D.E., Woodward, J.C. and Nicholas, A.P.: 1993, *Tracers in Hydrology (Proceedings of the Yokohama Symposium, July 1993)* IAHS Pub. No. 215, p329-338.
Walling, D.E. and Webb, B.W.: 1987, *Sediment Transport in Gravel-bed Rivers*. Ed. Thorne, C.R., Bathurst, J.C. and Hey, R.D. John Wiley and Sons. p691-723.