An investigation of flow-driven soil erosion processes at low stream powers

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Abstract

There is general agreement among researchers that at least for some time during erosion events sediment leaving an area is finer than that of the soil under surface erosion. But in some cases, it has been observed that coarser particles are transported at greater rates greater than fine. This paper reports on the results of an investigation into the processes that control the size distribution of the sediment during runoff erosion events at low flow rates and streampowers. Experiments were carried out on three contrasting soil types in the 1 x 6 m flume of Griffith University's large rainfall-runoff simulation facility at a slope of 2 percent, with overland flow confined to uniform rectangular rills pre-formed in the soil bed. The time variation in size distribution of the exiting sediment was measured for all experiments. The results supported a selective bimodal particle size class pattern for transported sediment with peaks for the finest size class of < 0.001mm and also for the larger class of 1-2 mm. Particles between 0.1-0.5 mm appeared to resist transportation. It seems that this selectivity in transport may indicate different transport mechanisms, such as suspension, saltation and rolling, can dominate in different sediment size classes, perhaps reflecting differences in resistance to transportation (or transportability) at the low streampowers investigated.

Keywords: Soil erosion, flow-driven, sediment size distribution, rill, rolling

1. Introduction

There is a need to describe sediment sorting if both on-site and off-site effects of soil erosion are to be understood. Many previous studies have investigated sediment sorting and tried to
determine the processes affecting it. Sediment leaving an eroding area is a combination of primary soil particles (sand, silt and clay) and secondary or aggregated soil material. There is general agreement among researchers that, at least for some period of time, sediment eroded from an area is finer than that of the eroding soil surface (e.g. Alberts et al., 1980, 1983; Foster et al., 1985). However, in some cases it has been observed that the sediment size distribution is bimodal with one small and one larger size class dominating the eroded sediment (Meyer et al. 1980; Loch and Donnollan, 1982). At the steady state condition, many researchers (Walker et al., 1977, 1978; Moss et al., 1979; Govers, 1985; Palis et al., 1990; Proffitt and Rose, 1991; Hairsine and Rose, 1991, 1992a, b; Beuselinck et al., 1999; Hogarth et al., 2004) have found that size distribution of the sediment is very similar to that of the original soil.

Multi-class erosion/deposition theories; such as the WEPP model (Nearing et al., 1989) and that of Hairsine-Rose (Hairsine and Rose, 1991, 1992a, b) are capable of simulating the size distribution of eroding sediment. In the WEPP model, empirical equations have been developed (Foster et al., 1985; Flanagan and Nearing, 2000) to calculate the fractions of five defined sediment classes. Based on Hairsine-Rose theory in which the source material is divided into an arbitrary number \( J \) of settling velocity classes with an equal mass of soil in each class, models of sediment sorting have been developed (Hairsine et al. 1999; Hairsine et al., 2002; Sander et al., 2002; Hogarth et al., 2004; Rose et al., 2006).

There are still some conflicting and unexplained results regarding the prediction of sediment sorting (e.g. Beuselinck et al., 2002; Rose et al., 2006). Sediment particle size distributions seem to depend on many factors such as the erosive agent (rainfall or runoff), flow hydraulic type (sheet or rill), flow and rainfall rate, slope and soil type. Rills commonly provide the dominant
transport network in eroding hillsides (Ruff et al., 2003), and the focus in this study is on understanding flow-driven erosion mechanisms in rills.

The existence and importance of bedload mechanisms such as rolling in sediment transport is not yet clear. There is also no clear reason for the bimodal sediment size distributions observed by some researchers, though the first peak for the fine particles could be interpreted by the saltation-suspension mechanism. This paper describes experiments on different soil types at low flow rates and streampowers, in which the time variation in size distribution of the exiting sediment resulting from flow-driven erosion was measured in some detail and this data used to interpret likely erosion mechanisms at work.

2. Materials and Methods

A series of experiments was carried out in the flume of the GUTSR (Griffith University Tilting Flume Simulated Rainfall) facility. This is a 1x 6m tilting flume with solid base with rainfall and runoff-runon facility (further detail being given by Misra and Rose, 1995). In all the reported experiments, flow was provided at the top of the flume at a constant rate with no added rainfall. Six experiments were carried out on three contrasting soil types, whose characteristics are given in Asadi et al. (2006). The first soil was a brown sandy soil classified as a Podzol (FAO, 1998) or Podsol (Isbell, 1996) which was treated by washing away the organic coatings of the sand particles and much of its clay fraction to yield a sand fraction of 94%. The second soil was a Red Earth classified as a Ferralsol (FAO, 1998) or Ferrosol (Isbell, 1996) with 43% clay, and the third soil a self-mulching black clay classified as a Vertisol (FAO, 1998) or Vertosol (Isbell, 1996) with 64% clay. These three soils will be referred to as Toohey, Red Earth and Black Earth respectively in this paper, for which the mean settling velocities were 0.065, 0.066, and 0.038 m s\(^{-1}\). Settling velocity was calculated using the equation of Cheng (1997).
Five experiments were carried out, with overland flow confined to uniform rectangular rills pre-formed in the soil bed. The three rill experiments on the Black Earth will be denoted by (R1, R2 and R3), the one on the Red Earth (R4) and one on the Toohey soil (R5). The details of the experiments including rill dimensions and flow rates are given in Table 1. Soils were freed of clods greater than 8 mm and un-decomposed plant residue. Soils were then formed into a level, 10 cm thick, soil bed in the GUTSR before being saturated for 12 hours with Brisbane town water and left to equilibrate for 2 days. The slope was the same (2%) for all experiments. Uniform rills were then artificially dug in the soil bed. Experiment duration was 15 minutes for R1, R2, R3, and R5 and 30 minutes for R4.

**TABLE 1 ABOUT HERE**

Runoff was periodically sampled to yield measurement of sediment concentration and the aggregate size distribution of eroded sediment leaving the flume during the experiments. The nest of sieves used in wet sieving were 4.0, 2.0, 1.0, 0.5, 0.25, 0.125, 0.075 and 0.038 mm size, respectively. Wet sieving commenced with the fast wetting (immersion wetting), and the duration of sieving for every sample was 10 minutes at a frequency of 35 RPM. After each experiment, the aggregate size distribution of rill bed samples taken to a depth of 4 mm was also determined by wet sieving.

The original uneroded soil was subdivided into $I$ size classes each having an equal mass fraction using the wet sieving data. $I$ was chosen to be 10 for the Black and Red Earth soils. However to more adequately represent the strongly sigmoid shape of the particle size distribution of the Toohey soil, $I$ was chosen to be 20. The fraction of each of $I$ size classes in the outflow sediment
at different times was then obtained using the subdivision of equal classes obtained for the
original soils as described in Asadi et al (2006).

One more experiment of a different type was carried out on the Black Earth at a slope of 2.5% in
which a unit inflow discharge of 0.0002 m$^2$ s$^{-1}$ was delivered uniformly to the upper end of
flume. Runoff in this experiment was in sheet form over the entire length (6 m) and width of the
flume (1 m) during the first 15 minutes of the erosion process, at which point a rill started to
form naturally, and was allowed to develop and extend to the flume exit, and the erosion process
followed for another 20 minutes. This experiment is referred to as the SR (sheet to rill)
experiment. During the sheet flow condition of this experiment (first 15 minutes) water depth
and stream power were 4.5 mm and 0.04905 W m$^{-2}$, respectively. Runoff sampling and sample
treatment for this experiment were somewhat different from the other experiments. Soils were
freed of clods greater than about 4 mm for this experiment, and the nest of sieves used in wet
sieving were of 2, 1, 0.5, 0.25, 0.125, 0.075 and 0.038 mm sizes, respectively. Therefore, the 10
size classes identified for this experiment were different from those obtained for rills R1, R2 and
R3.

3. Results

Figs. 1a, 1b and 1c show the mass fractions of each of the 10 size classes in the outflow at three
different times for all rill experiments (R1, R2 and R3) on the Black Earth soil. The original un-
eroded soil consisted of 10 equal mass fractions in each size class, indicated in Fig 1 by a
uniform original fraction of 0.1. Sediment fractions greater than 0.1 can be said to be
preferentially transported (Fig 1).
For the three experiments on the Black Earth the earliest measurements were made at 3.5 minute for R1 and 2.5 minutes for R2 and R3. Figs. 1a, b, c show that regardless of this minor difference in early sampling times, the sediment size distribution is bimodal with peak fractions for the finest class of 0.001 mm and the large size class of 2.07 mm. Fractional sediment concentration was lowest at 0.16 mm and 4.5 mm (Figs. 1a, b, c). The size class of 2.07 mm alone included 30 percent of the total sediment loss at the earliest time of 3.5 minutes for R1, at which time the size class of 0.16 mm was transported at a rate 14 times slower than for the 2.07 mm class (Fig. 1a).

The theory of Rose et al., (2006) suggests that for sediment transported by saltation, the mass fraction of finer sediment is expected to decline with time. Indeed the data in the Fig. 1 and Fig. 2 demonstrate this expectation. In contrast the time variation in mass fraction for larger sediment is not entirely consistent (Figs. 1 and 2). At earlier sampling times the distribution of mass fraction with size class is distinctly bimodal in Figs. 1 and 2b, whereas the dominant feature in Fig. 2a is the dominance of the smallest fraction. The bimodal nature is due to the high mass fraction of the smaller size classes (Figs. 1, 2). As time proceeds in the erosion event, the somewhat rapid decline in the finer mass fractions softens the bimodal nature of the distribution with size class, whilst a range of larger size classes have their mass fractions enhanced above the fraction expected from the size distribution of the original soil. Between these two over-represented or enhanced low and higher size class ranges is a region of sediment size classes (around 0.16 mm in Figs. 1a and 1c for example) which evidently provide a higher resistance to transportation as evidenced by their lower mass fractions. Differences between results shown in Fig. 1 and 2 are in the degree and size of range of preferential sediment transport, indicated by a
mass fraction exceeding 0.1 in the case of Black Earth and Red Earth soils, or 0.05 for Toohey soil (Fig. 2b).

FIG. 2 ABOUT HERE

To complement the pattern of transported sediment described earlier, the particle size distribution of the rill bed was experimentally determined after each experiment. The least transported classes of particles would be expected to have accumulated on the surface of soil bed, and the soil bed should been depleted in selectively transported particles. The particle size distributions of the rill beds sampled after each experiment are shown in Fig 3. For all experiments, the rill bed has been depleted of the finest particles (Fig. 3), the fraction which created the first peak of sediment size distribution in Figs. 1 and 2. Particle size distribution of the rill beds show a peak at about 0.16 mm for Fig. 3b and 3c, with a somewhat wider range of elevated values for Fig. 3a. The size class around 0.16 mm generally had the lowest fraction in outflow sediment for most of the experiments as shown in Figs. 1 and 2. Thus, in general terms those fractions less well represented in eroded sediment were found to be most common in the soil bed following the experiments.

The low fraction of the coarser class (4.5 mm) found in the beds was not expected, but may be an artifact of sampling. When the soil surface was sampled for analyzing particle size distribution after the experiment, samples were taken as thin as possible (3-4 mm), thus probably excluding particles larger than this (Fig. 3). Therefore, especially for larger particles, the fractions presented in Fig. 3 do not have the same precision as fractions given in Figs. 1 and 2.

FIG. 3 ABOUT HERE
Fig. 4 (a-c) shows the results for the last (and different type) of experiment (SR) carried out on the Black Earth. In this experiment flow was in sheet form of 1 m wide until about minute 15, when a rill initiated naturally in the middle of the flume, and developed and extended to the flume exit, being sampled until minute 35. Thus this experiment investigates the change in sediment characteristics during and following the transition from sheet to rill erosion. Sediment concentration at the initial approximate steady state before rill initiation is about 0.6 kg m$^{-3}$ (Fig. 4a). During the sheet flow the stream power is about 0.049 W m$^{-2}$. Fig 4b shows that prior to rill initiation (at minutes 4.5 and 14), about 90 percent of sediment is in the finest class, and in larger size classes there is some decrease as particle size range increases. However when a rill developed in the middle of the flume, sediment concentration increased, first slowly and then rapidly as shown in Fig. 4a. By full rill development after 35 minutes, the mass fraction of larger particles had increased substantially (see Fig. 4b). As was the case for the previously described experiments, the size analysis of what is left behind on the rill bed (Fig. 4c) generally (though not exactly) supports the expected consequences for the bed sediment of the selectivity in transportation discussed earlier.

FIG. 4 ABOUT HERE

4. Discussion

Possible reasons need to be examined for the observed differences between the size fractions of eroded sediment and their change with time (Figs. 1, 2 and 4b). Such differences in eroded sediment would be expected to have complementary consequences for the surface layer of sediment left behind in the soil bed (Figs. 3 and 4c).
Based on the results of prior research (e.g. Loch and Donnollan, 1982; Proffitt and Rose, 1991; Rose et al., 2006), the size distribution of sediment leaving an eroding area of soil could be influenced by the following factors: (a) the particle size distribution of the original soil, (b) the settling velocity of different size classes of particles, (c) aggregate breakdown during erosion, and (d) selective transport of various size fractions. The possible role of each of these four factions will now be considered.

(a) As explained by Asadi et al. (2006) the effects of particle size distribution of the original soil were effectively eliminated by dividing the size (or settling velocity) distribution of the original soil into an arbitrary number ($I$) of size classes, each of equal mass. “$I$” = 10 was used for the Black Earth and Red Earth soils, so that if the size distribution was unaffected by erosion, each sediment fraction would be 0.1 (Figs. 1, 2a, 3a,b)

(b) Many experiments have shown that during flow-driven (as well as rainfall-driven) erosion sediment is enriched with finer particles at early times (e.g. Walker et al. 1977, 1978; Moss et al. 1979; Alberts et al. 1980, 1983; Proffitt and Rose, 1991). These experimental observations are interpreted by theory (Rose et al. 2006), which shows that when the erosion processes are dominated by suspension and saltation, and if soil entrainment and re-entrainment processes are assumed to be non-selective with respect to size class, then this initial fine nature of sediment is predicted to occur. Not only is the initially finer distribution predicted to become coarser with time, but that at equilibrium the distribution should become the same as that of the original soil (assuming no structural breakdown) (Rose et al. 2006; Hairsine and Rose, 1992a,b).

The reduction through time in proportion of the finer fractions illustrated in Figs. 1 and 2 may be due to this expected role of size (or settling velocity) during suspension/saltation. Though not
entirely convincing, the size distribution at the longest time of measurement tends to be closer to that of the original soil than at earlier times (an equilibrium theory prediction). However the saltation/suspension theory is quite unable to explain the bimodal pattern of sediment transport shown in Figs. 1 and 2, in particular that the fraction of somewhat larger particles can exceed that present in the original soil.

In conclusion, There is some evidence based on Figs. 1 and 2, and the non-equilibrium flow-driven erosion theory of Rose et al. (2006), that the size (or settling velocity) distribution of the original soil does play a role in explaining the observed results. However the bimodal pattern of fractional distribution cannot be understood on this basis.

(c) In all experiments, the erosive agent was flow alone (not rainfall), the soil bed was pre-saturated before each experiment, and both the flow rates and the slope of the soil surface (2%) were low. Thus whilst aggregate breakdown cannot be discounted, it is less likely to be a major factor affecting size distribution during erosion. The Toohey soil was freed of water stable aggregates prior to use in experiments, so that aggregate breakdown can be entirely discounted for this soil. Note that for this soil the general pattern of change in sediment size characteristics shown in Fig. 2b was similar to that of the other two structured soils (Figs. 1 and 2a).

If it occurred, structural breakdown would tend to reduce the fraction of larger sediment size classes (likely to be aggregates in the structured soils), and thus finer fractions would be enhanced. Figs. 1 and 2 show that, for all but the largest size fraction, the larger soil fractions exceed that of the original soil (0.1 or 0.05 for the Toohey soil). This finding does not support structural breakdown as an important mechanism.

(d) The three previously considered factors (a) to (c) cannot provide an explanation of the bimodal sediment size distribution shown in Figs. 1 and 2. Also, Fig. 4 illustrates that the flow
velocity increase associated with the transition from sheet to rill erosion is accompanied by a
dramatic change in the size distribution of eroded sediment, with mobilisation of larger
aggregates which were at quite low mass fraction during sheet flow (Fig. 4b).
Combined, these observations strongly suggest that at least in the low stream power range
investigated in these experiments another erosion mechanism not so far incorporated in
commonly used theory could be active, a process which depends on flow velocity or stream
power, but which is more effective in transporting larger sediment size ranges. This feature
suggests the mechanism of bed-load transport such as rolling, and indeed rolling of relatively
larger particles was observed and recorded in video images taken during the reported
experiments. Simple theory also suggests that the drag force on a particle could increase with
particle size and flow velocity.
Moss et al. (1979) noted that sediment transport can be divided into suspended, saltating and
contact (rolling) loads, each normally being broadly associated with particular sediment size
ranges. Cummings (1981) suggested that particles < 0.031 mm move mostly as suspended load;
those between 0.031 and 0.211 mm, through saltating bed load, and those > 0.211 mm through
contact bed load. The upper boundary for suspended load was chosen to be 0.02 mm by Loch
and Donnollan (1982), who also indicated a transition from saltating to contact load in the size
range of 0.125-0.250 mm. Our results support the existence of such boundaries, with the addition
of another upper size boundary for cessation of bedload transport which is evidently greater than
5 mm (Figs. 1-4). The resistance to flow of the largest particles used in this set of experiments
(4.5 mm), is likely to be due to their large immersed weight. Data on flow driven erosion from
the Red Earth used in these experiments is given by Rose et al., (2006), showing changes
through time in sediment concentration and settling velocity characteristics (dominated by
changes in sediment size distribution). Theoretical predictions of these dynamically changing
soil characteristics based on saltation theory alone were compared with experimental data. This
comparison indicated the likelihood that another erosion process in addition to saltation could
well be acting and becoming more important with time during erosion. Published data of this
detailed type is not common.

Considering suspended load and saltating load as a single mechanism (suspension-saltation), data
in Figs. 1 and 2 suggest 0.16, 0.28 and 0.25 mm for the Black Earth, Red Earth and Toohey soil
respectively as the approximate particle size beyond which bed-load transport starts to become a
significant additional mechanism of sediment transport. This suggests that the boundary between
suspension/saltation and bed load dominance as transport mechanisms can depend on soil type.
However this boundary could also depend on stream power, (on which sediment erosion depends
(Proffitt et al., 1993)), noting that stream power varied from 0.076 to 0.246 W m$^{-2}$ for the three
soils (Table 1). During experiment SR the naturally induced transition from sheet flow to rill
occurred at a stream power of about 0.05 W m$^{-2}$ for unconsolidated soil, though this magnitude
would be expected to increase with soil strength (Misra and Rose, 1995). Using data from Table
1, and using mean weight diameter as grain size, then the Shields-type curves for quartz-density
solids (Allen, 1985) indicates no sediment motion under these flow conditions, whereas the
Hjulstrom curve for rivers indicates transport would be as bedload.

The hypothetical diagram presented as Fig. 5 provides a plausible suggestion on how these two
erosion mechanisms may overlap and complement each other. Importantly Fig. 5 also suggests a
reason for the bimodal nature of the particle size of eroded sediment which has been noted as a
consistent feature of the experimental data presented in Figs. 1, 2 and 4. In modeling
transportation of soil particles, therefore, we may need to consider different stream power or
shear stress thresholds, (perhaps in combination with particle size), for dominance or development of different erosion mechanisms. Support for the suggestions illustrated in Fig. 5 awaits the development and testing of new dynamic theory.

FIG. 5 ABOUT HERE

The results of experiment SR presented in Fig. 4 also show that in the earlier stage of sheet erosion suspension-saltation appears to be the most active mechanism, since most sediment transported is in the finest fraction. With the concentration of flow as the rill develops, the stream power of flow will increase and the observed rolling mechanism appeared to become dominant.

The distribution of sediment mass fraction among the size classes then again becomes bimodal (Fig 4b), presumably because both suspension/saltation and bed load transport mechanisms are active (see Fig. 5). The results in Figs 1, 2 and 4 also provide a reminder that the effects of non-steady or transient effects also need to be recognized, although further theory development of such dynamic effects is beyond the scope of this paper.

Fig. 4a shows that after natural rill development the sediment concentration at 35 minutes was about 6.7 kg m\(^{-3}\), comparable with 7.1 kg m\(^{-3}\) for experiment R3 on the same Black Earth soil (see Table 1). Comparing the mass fraction distribution for the corresponding figures 4b (at 35 minutes), and 1c (at say 14 minutes), there are similarities (and minor differences) in the typical somewhat bimodal mass fraction distributions. This suggests that whether rills are pre-formed (as in experiments R1 to R5), or are allowed to develop naturally (as in experiment SR), in each case the eroded sediment exhibits a similar characteristic bimodal type of mass fraction distribution. Thus this characteristic, suggestive of the operation of two types of sediment
transport mechanisms, appears not to be simply a feature of the pre-formed rills used in most of
the reported experiments (R1 to R5).

The very high mass fraction of the smallest component during the initial sheet flow period of the
SR experiment shown in Fig. 4b indicates a dominant sediment transport by this fraction, and its
rapid decline in time is theoretically expected if suspension/saltation is the dominant transport
mechanism (Rose et al., 2006).

5. Conclusion

Under flow-driven erosion at low stream powers the size distribution of sediment from these soil
types was found to develop through time, resulting in a bimodal type of mass fraction
distribution. This characteristic behavior is shown not to result from the size distribution of the
original soil, nor is it all likely to have been the result of aggregate breakdown during erosion.
Change with time in the size fraction at earlier times was consistent with expectation, based on
theory and common experimentation, that the decrease with time, especially in the finer fractions
is an expected consequence when suspension/saltation is the dominant erosion mechanism.
However the observed development with time in a persistent bimodal character of the size
distribution indicates that some mechanism in addition to suspension/saltation must be active in
selectively enhancing the transport of medium to larger sized sediment particles or aggregates.
Direct observation and video recording indicated that this often neglected mechanism involved
the rolling or bed-load transport of larger sediment.
An experiment in which a major increase in streampower accompanied the transition from sheet
to rill erosion supported the concept that some threshold in streampower needs to be exceeded
for rill development to occur.
A hypothetical model is given suggesting that when, through time, suspension/saltation becomes less dominant, then bed-load transport or rolling of medium to larger sized aggregates increasingly becomes the dominant transport mechanism, in turn becoming less effective for very large sediment.

Acknowledgments
The assistance of Dr. H. Rouhipour is gratefully acknowledged. The first author thanks the Iranian Ministry of Science, Research and Technology for the opportunity to study at Griffith University in Australia during his PhD degree.

References


Fig. 1. Mass fractions of the 10 size classes in outflow sediment at the different times for three rill experiments carried out on a Black Earth, (a) R1, (b) R2, and (c) R3.

Fig. 2. Mass fractions of the I size classes in outflow sediment for the experiments on (a) the Red Earth (R4), and (b) Toohey soil (R5) at the different times.

Fig 3. Fractions of various size classes in rill bed after the experiments for (a) R1, R2 and R3 on the Black Earth, (b) R4 on the Red Earth, and (c) R5 on the Toohey soil.

Fig. 4. The results for experiment SR with Black Earth showing: (a) changes with time in sediment concentration, (b) changes with time in individual mass fraction of various size classes before and after rill development and (c) individual mass fraction of various size classes in the rill bed after experiment.

Fig. 5. A hypothetical diagram showing the possible effects of suspension-saltation and bed load mechanisms in transporting of various size classes of soil particles following development of a bed-load component.