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Direct measurement of in-channel abrasion processes

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ABSTRACT Downstream trends in the bed sediment character of alluvial channels are attributed to hydraulic sorting and mechanical abrasion processes acting within the channel. Historically, abrasion processes have been isolated in the laboratory by use of abrasion tanks and tumbling barrels. However, laboratory abrasion rates are commonly lower than those observed in the field, and Schumm and Stevens (1973) proposed that "abrasion in place" processes may also operate within the channel. Thirty nine mobile and semi-mobile tracers were seeded in two selected reaches of the Plynlimon Experimental Catchments, to directly measure the abrasion of individual test clasts in the natural channel environment. Significant weight losses (~0.5g) sustained by tracers above the bed load trap, tracers fixed directly to bedrock, and tracers tethered confirmed the potential importance of over-passing bed load as an abrasion process. Weight losses sustained by tracers below the bed load trap (~0.05g) also indicated the potential of "sandblasting" as an additional "abrasion in place" process.

INTRODUCTION

Downstream changes in the sediment characteristics of rivers are commonly explained in terms of selective entrainment, transport, and deposition (hydraulic sorting), or the physical modification of clasts themselves whilst mobile (mechanical abrasion). Historically, abrasion processes have been isolated in the laboratory by use of tumbling barrels (Daubree, 1879; Marshall, 1927; Bigelow, 1984) and abrasion tanks (Kuenen, 1956b; Bradley, 1970; Bradley et al., 1972). Clast weight losses per unit distance, observed by these workers under laboratory conditions, were consistently lower than downstream reductions in weight loss derived from field sampling (Bradley, 1970; Schumm and Stevens, 1973; Adams, 1978; Adams, 1979). The observed discrepancy between laboratory and field sediment reduction rates has commonly been attributed to hydraulic sorting processes

(Mackin, 1963) or weathering (Bradley, 1970), but Schumm and Stevens (1973) proposed an alternative theory of "abrasion in place", whereby clasts are abraded by vibration within the bed without net downstream movement.

Laboratory simulation of this vibration yielded promising results (see Schumm and Stevens, 1973), but no subsequent research relating to "abrasion in place" processes has been reported. Nor did Schumm and Stevens actually observe and report significant abrasion occurring in their experiments. If such processes operate within the natural channel environment, they have implications for theories on hydraulic sorting, in that particle size can be reduced in situ without selective hydraulic sorting processes operating, or down-channel transfer of the clasts being required. Therefore, a tracer study was undertaken in order to quantify the abrasion of individual test clasts in the natural channel environment. It is believed that this paper reports detailed direct abrasion observations in field situations for the first time.

FIELD SITES

The study reaches were all within the Institute of Hydrology experimental catchments, Plynlimon (see Kirby, Newson and Gilman 1991). The catchments contain intensive hydrological, water quality and sediment monitoring networks (Leeks and Roberts 1987, Leeks 1992). The streams are typical of upland Wales, with irregular plan and cross-sectional form, strongly influenced by large glacially derived boulders and bare rock outcrops within the channels (Newson 1981). The local hard rock geology is of Ordovician and Silurian mudstones and shales and much of the bed-load is made up from this material and reworking of fluvio-glacial material of similar composition.

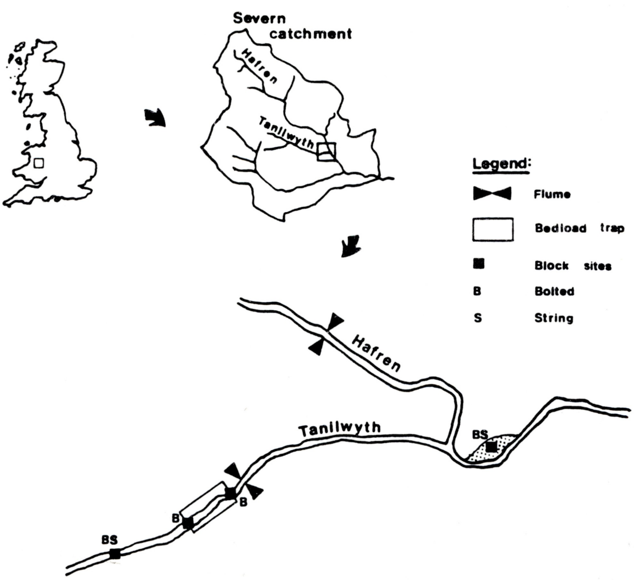

FIG. 1 Location map and diagram of study sites.

The climate is temperate with 231 rain days and mean annual precipitation of 2449mm.The sites of study shown in Figure 1 are at an approximate height of 350m A.O.D. The lowest site is on the river Hafren (Severn), with a catchment area of 4.57 km^2. The Hafren tracers are positioned on a point bar immediately opposite a photo-electronic bank erosion monitoring site. The majority of the sites are on a Hafren tributary, the Tanllwyth, with a catchment area of 0.89 km^2. Tracers were bolted to the upstream and downstream aprons of the Tanllwyth bed load trap and in the reach immediately upstream of the trap.

METHODS

Tracers were 25mm rock cubes sawn from large pieces of parent rock. Extensive laboratory simulation of abrasion processes has demonstrated that for a given lithology, rock cubes exhibit similar weight loss patterns and rates to natural channel material (Brewer, 1991) Cuboid tracers have several advantages over natural tracers in such a study: first, clast size is standardised thus eliminating differences in surface area between tracers. Second, loss of a single edge or corner dimension is simple to monitor. Finally, impact marks on the cube faces are easy to distinguish, aiding interpretation of bedload movement events.

Instead of using conventionally seeded clasts which are mobile within the channel, the seeded clasts were either bolted to immobile objects (bedrock or 450mm x 220 mm x 100 mm concrete blocks) or tethered to immobile objects by string. The clasts that were fixed and static would only be abraded by bed material passing over them, whereas the semi-mobile clasts (those tethered by string) would be abraded by bed material movement and by virtue of their own limited movement. Table 1, Table 3 and Figure 1 illustrate the fixing procedures and locations and also the cube lithologies selected for the five test sites. Recovery rates of the fixed cubes were high after the first flood event. However, two of the bedrock cubes on the Tanllwyth were not recovered, as a result of the cubes splitting and becoming detached.

TABLE 1 Lithologies of tracer clasts.

Lithology / Code No.
Aberystwyth Grit / 72a
Old Red Sandstone / 75
Carboniferous Limestone / 80b
Chinastone / 82b
Permo-Triassic Sandstone / 89a
Carboniferous Chalk / 106a

TABLE 2 Hydrological data for the Tanllwyth Flume over the six week experimental period.

EVENT NO. (Dates)	PEAK RAINFALL (mm) (Date)	PEAK DISCHARGE (m^3s^{-1}) (Date and Time)
1	75.0	1.904
(19th-22nd Dec.)	(20-12-90)	(21-12-90, 4-30 pm)
2	33.4	0.950
(24th-26th Dec.)	(25-12-90)	(27-12-90, 9-15 am)
3	48.2	1.652
(1st-4th Jan.)	(1-1-91)	(1-1-91, 7-30 pm)
4	29.0	0.433
(7th-11th Jan.)	(9-1-91)	(9-1-91, 8-15 pm)

TABLE 3 Weight losses (g) of individual tracers over the six week experimental period at the Tanllwyth (Tan) and Hafren (Haf) study sites.

LOCATION	LITHOLOGY					
	72a	75	80b	82b	89a	106a
Above Trap (Tan)	0.02	0.08	2.25	0.61	2.44	3.59
Below Trap (Tan)	0.00	0.05	1.87	0.08	0.02	1.60
Block	0. 0.03	0.11	0.56	0.23	0.18	0.43
/ String (Tan)	0.03	0.09	0.45	0.15	0.04	0.47
Block	0. 0.04	0.08	0.50	0.11	0.04	----
/ String (Haf)	0.04	0.07	0.49	0.05	0.02	----
Bedrock (Tan)	5 clasts Old Red Sandstone (Lithology 75)					
	----	0.58	0.58	----	0.18	

Examination of Table 3 indicates that rates of weight loss differ between the tracer types. First, regardless of lithology, weight losses are consistently higher above the bed load trap than below it. Second, regardless of lithology, weight losses are generally higher for tracers fixed to concrete blocks than for those tethered by string. Finally, weight loss rates for Old Red Sandstone (75) were highest for those tracers fixed directly to bedrock in the Hafren. Interpretation of these results can be made in terms of bedload movement and the nature of "abrasion in place processes".

DISCUSSION OF RESULTS

The semi-mobile and fixed tracers were placed in the Tanllwyth and the Hafren on the 13th December 1990, and were retrieved for re-analysis on the 23rd January 1991. During this six week period, rainfall events produced four stream discharge peaks capable of causing bedload movement (Figure 2). Tables 2 and 3 provide hydrological data for these events and summarise the weight losses sustained by the various tracers. Although hydrological data is not presented for the Hafren, its proximity to the Tanllwyth ensures a similar precipitation pattern. However, the Hafren is a significantly larger catchment than the Tanllwyth, and this results in the Hafren having peak discharges at least double those observed on the Tanllwyth.

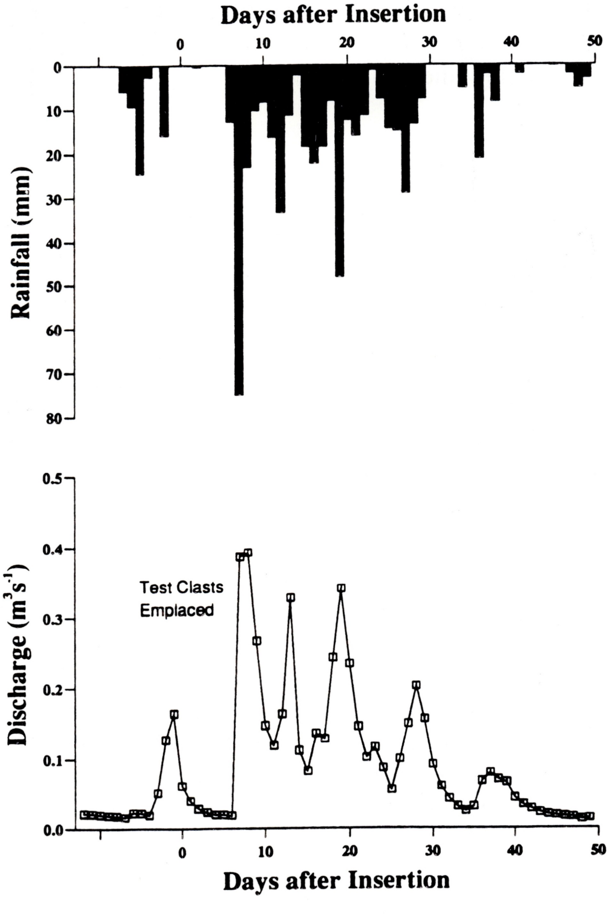

FIG. 2 Tanllwyth hydrograph and rainfall plot for the 1990/1991 tracer experiment.

Bed load Trap

During the experimental period, 2.18 tonnes of sediment were deposited in the bed load trap, and this sediment was therefore also transported over the fixed tracers on the upstream apron of the bed load trap. Figure 3 illustrates the particle size distributions for the Tanllwyth channel gravels and for the sediment collected from the bed load trap. The channel sediments range from very coarse gravel to fine gravel, and are normally distributed with a mean particle size of -5.63 Φ (49.45 mm). The bed load trap sediment has a significantly different particle size distribution (Figure 3B); this is partly a result of the data being presented as percentage weight per size grade and not clast frequency per size grade. However, Figure 3 demonstrates that the coarsest material transported by the four discharge events had a maximum diameter of -6 Φ (63 mm), whereas the coarsest component of the channel sediment had a mean diameter of -8 Φ (256 mm). In addition, there was a significant percentage of fine gravels and sands in the trap (>20%), size grades that were not present in the surface gravels of the channel sample. An important question is: How do these bed load characteristics relate to the abrasion of fixed tracers above and below the bed load trap?

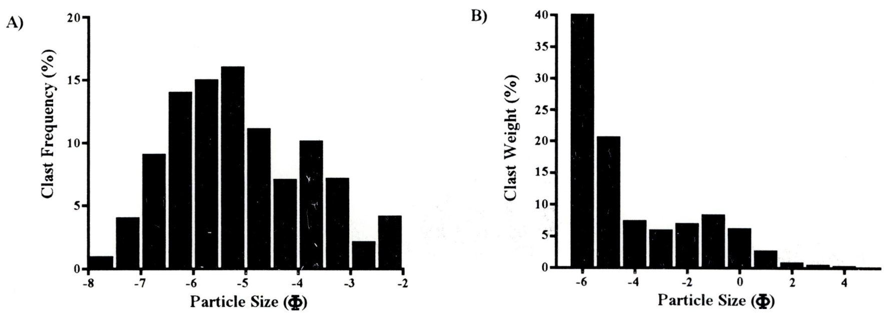

FIG. 3 A) Particle size distribution for the Tanllwyth channel sediment. B) Particle size distribution for the bed load trap sediment.

The large bed load trap acts as a sediment sink, that is, unless the trap becomes filled with sediment, very little bed load is transported through it. Below the bed load trap, wear rates were very low (Table 3), and there was little visual evidence of abrasion. Weight losses were highest for the two carbonate lithologies (80b and 106a); this was a result of solution processes in the acidic stream water. The small weight losses sustained by the other lithologies are likely to be the result of blasting by the sand component of the suspended or saltating load (cf. Kuenen, 1956a), since abrasion cannot be the result of bed load movement on the downstream apron of the trap.

Above the bed load trap, weight losses were relatively high (Table 3), and distinct abrasion patterns were evident on the tracers. Weight losses were even higher for the carbonate lithologies (80b and 106a), and the mechanically weak Permo-Triassic Sandstone (89a) also lost considerable mass. Eliminating the solution component from the upstream carbonate tracers, all tracers above the trap lost weight at a faster rate than tracers below the trap. Abrasion patterns on the tracers were also well developed above the trap. Two lithologies (89a and 106a) exhibited large corner chips, and all lithologies exhibited smaller scale chipping of edges which faced upstream.

These results give credence to the theory of "abrasion in place", that is, clasts which are static on the bed, but which have sediment passing over them, can be subject to significant abrasion. Such a process would be most likely to occur on larger clasts, which are mobilised less frequently. In addition, the slight weight loss of non-carbonate rocks below the trap indicates that abrasion by suspended material may also contribute to clast abrasion.

Concrete Block / String

It was originally hypothesised that tracers fixed to the concrete blocks would be exposed only to bedload abrasion, and that tethered tracers would be additionally exposed to abrasion by virtue of their own limited movement. Therefore, one would expect weight losses for the tethered tracers to be higher than for the concrete block tracers. However, in general the weight loss pattern was the reverse on both the Tanllwyth and the Hafren (Table 3). Observation of the tethered tracers indicated that wear was non-existent on edges and only very slight on corners. By contrast, concrete block tracers exhibited significant corner chipping and slight edge chipping.

There are two possible explanations for the relatively slight wear of the tethered tracers. First, although the concrete blocks were initially set flush with the stream bed, scour around the blocks caused a "lee" downstream where flow velocity and thus bed load movement were reduced. Second, the tracers became buried within the bed-sediments, thus shielding the tracers from further abrasion. This does not suggest that vibratory action was not effective.

Weight loss rates for these two tracer types are generally similar between the Tanllwyth and the Hafren, but weight losses are significantly higher on the Tanllwyth for two lithologies (82b and 89a), a surprising result, since discharges are much higher on the Hafren. Weight losses for the two "hard" lithologies (72a and 75) compare favourably with the rates observed above the bed load trap, re-enforcing the theory that the majority of weight loss sustained by fixed tracers is a result of bed load movement.

Bedrock

The Old Red Sandstone (75) tracers sustained the highest weight loss when fixed directly to bedrock on the Tanllwyth. The bedrock outcrop in the channel represents a local steepening of the channel gradient, and is thus an area of sediment transfer rather than deposition. Two tracers were lost at this site, probably a result of the tracers splitting. Weight loss of the most downstream tracer was under a third that sustained by the two remaining upstream tracers on the bedrock outcrop. All three tracers exhibited major corner and edge rounding on their upstream sides, with small scale chipping also on the upstream face.

One might have expected the weight loss of tracers fixed to bedrock to be similar to the weight loss of tracers fixed to the upstream apron of the bed load trap, since they both represent zones of rapid sediment transfer. However, abrasion of the bedrock tracers may have been enhanced by local "focusing" of bedload movement over the bedrock outcrop, or alternatively, local bed load discharge may have been higher at this site. Even though the weight loss rates do not correlate between these two sites, evidence consistently suggests that abrasion of static clasts by bedload movement can be a significant cause of weight loss in the natural channel environment.

CONCLUSIONS

Use of fixed and semi-mobile tracers has demonstrated that clasts can be subject to abrasion by over-passing bedload. Although weight loss rates are low (< 0.5 g over several discharge events), the cumulative effects of such a process may be more significant, especially for larger clasts which are infrequently mobilised. The abrasion in place processes monitored in this study (bed load over-passing and sandblasting) are not the same as the "vibratory" process proposed by Schumm and Stevens (1973), suggesting that abrasion in place processes may be multi-faceted. Quantification of "abrasion in place" processes in the natural channel has implications for downstream fining processes, and consideration should be given to including it as a component in future models. This type of fixed tracer study may provide additional useful parameters in broader integrated fluvial sediment monitoring programmes.

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