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Shape and Size Characteristics of Bedload Transported During Winter Storm Events in the Cwm Treweryn Stream, Brecon Beacons, South Wales

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Abstract: Bedload transport in the Cwm Treweryn stream, a tributary of the Usk in the Brecon Beacons, South Wales, was investigated during a wet winter period in early 1995 using basket-type bedload traps and the tracing of painted clasts. The Cwm Treweryn is a typical mountain stream of the region with its gravel-bedload, flashy regime, high gradient and pool-riffle sequences. In particular, the study explored – for a range of categories of clast size – the nature of any influence of clast shape on bedload movement. Competent flows ranging from 2.5 to 19.5 $m^3 s^{-1}$ (the latter close to bankfull flow) were monitored. The size composition of trapped bedload clasts varied little with peak flow magnitude except for the very largest clast fraction, suggesting that bedload transport was strongly influenced by movement of the dominant small cobble fraction. Shape composition of trapped bedload was compared with sampled bed material from the reach immediately upstream. For the large gravel fraction (32–64 mm), discs were twice as frequent and spheres 5% more frequent than in the upstream reach material. Rods were greatly under-represented. Discs were 10% over-represented in the small cobble fraction (64–128 mm) and dominant (though not over-represented) in the large cobble fraction (> 128 mm), in which spheres were distinctly over-represented and blades absent. The transported material was rounder and somewhat more spherical than the reach material. The percentage of spherical large gravel and spherical and rod-shaped small cobble clasts increased with peak discharge, whereas discs of all sizes tended to decline with peak discharge. Blades are over-represented in medium events but not moved in smaller competent events, and are under-represented at very high flows. In painted-clast experiments, blades – and to a lesser extent – discs moved shorter distances than spheres and rods of similar weight. Overall, the results suggest that the influence of clast shape on selective transport becomes much clearer with increase of clast size relative to the bed roughness elements. On rougher beds, on the other hand, the apparent behaviour of any particular shape may be the result of the behaviour of other shapes.

Key Words: bedload, gravel-bed streams, particle shape, particle size, sphericity, Usk river, Cwm Treweryn stream, Wales

Güney Galler'in Brecon Beacons Yöresinde Bulunan Cwm Treweryn Akarsuyu'nda Taşınan Yatak Yükü Malzemesinin Şekil ve Boyut Özellikleri

Özet: Birleşik Krallık'ın Güney Galler bölgesi, Brecon Beacons yöresinde, Usk Nehri'nin kolu olan Cwm Treweryn akarsuyunda 1995 yılının yağışlı geçen ilk döneminde, sepet-biçimli yatak yükü tuzakları kullanılarak yatak malzemesi yükü taşınma şekilleri incelenmiştir. Çalışmada özellikle belirli oranlardaki çakıl boyut grupları ve çakıl şekillerinin taşınma üzerine olan etkileri (seçici taşınma) incelenmiştir. 2.5 ile 19.5 debiler arasında değişen güçlü akıntılar kaydedilmiştir. Oldukça iri boyuttaki yatak yükü hariç tutulduğunda, yakalanan çakılların boyut özelliklerinin yüksek debi oranlarıyla çok az bir değişme gösterdiği tespit edilmiştir. Bu durum yatak yükü taşınmasının, yatakta hakim olan küçük boyuttaki çakılların hareketleri şiddetli olarak belirlemektedir. Hareket eden yatak yükünün şekilsel özellikleri hemen civardaki yatak material yüküyle karşılaştırılmış olup, bulgular, iri çakıllar (32–64 mm) içerisinde disk şekilli materyalin oranı yatak yükünü teşkil eden malzemeye oranla iki kat daha fazla, küremsi olanların oranı %5 daha fazla ve ovalımsı şekildeki çakılların oranının ise daha az olduğunu göstermiştir. Küçük bloklar (64–128 mm) içerisinde ise disk şeklindeki hareket eden materyalin oranı yatak yükünü teşkil eden malzemeye oranla %10 daha fazla, iri bloklar (> 128 mm) içerisinde ise egemendir. Aynı şekilde, bu grup içerisinde küremsilerin oranı en fazla buna karşılık yassı şekilli hiçbir iri blok hareket etmemiştir. Hareket eden materyal içerisinde, iri çakıllar grubunda küremsilerin ve iri bloklar içerisinde ise küremsi ve oval şeklindeki materyalin yüzde oranı artan debi ile birlikte artma göstermiştir. Boyanmış taş deneyleri ile ilgili olarak, yassı ve disk şeklindeki taşlar eşit ağırlıklara sahip olmalarına rağmen küremsi ve ovalimsi taşlara oranla hareket mesafeleri daha kısa olmuştur. Bulgular genel olarak gösteriyor ki, çakıl boyutunun üzerinde hareket ettiği pürüzlü yatak yüzeyi elemanlarına oranla daha büyük olduğu durumlarda, çakıl şeklinin seçici taşınma üzerindeki etkisi daha belirgin olmaktadir. Buna karşılık, oldukça pürüzlü yatak yüzeyleri üzerinde, herhangi bir şekle sahip çakılın hareketi yatak yüzeyini oluşturan unsurların hareketi ile sınırlıdır.

Anahtar Sözcükler: yatak yükü, çakıl ağırlıklı akarsular, çakıl şekli, çakıl boyutu, yuvarlaklık, küresellik, Usk Nehri, Cwm Treweryn akarsuyu, Galler

Introduction

Sediment transport is an important process in fluvial geomorphology. Despite a considerable body of literature on sediment transport, many problems in river management continue to arise from the inadequate prediction of sediment behaviour during flood flows. In most environments, particularly in lowland regions, bedload is the least important of the three components of transport. However, in mountainous environments, where the supply of coarse material from the slope system is high, the bedload may exceed the combined dissolved and suspended loads (Lane & Borland 1951; Simons & Şentürk 1977; Hayward 1980; Lauffer & Sommer 1982; Thompson *et al.* 1992). In general, bedload will rarely include clasts less than 0.1–0.2 mm in diameter, because once disturbed smaller particles tend to go directly into suspension (Sundborg 1956).

Bedload transport in upland streams and rivers has gained the attention of earth scientists and engineers for the following reasons: (1) sustained interest in bedload developed as a result of the need to understand sediment transport in navigable channels (Du Boys 1879; Davis 1900); (2) bedload transport is the principal process linking channel form and hydraulics; morphological change (including bank erosion) in rivers is largely governed by bedload transport (Gomez 1991); (3) engineering projects require an understanding of sediment movement in channels transporting predominantly coarse-bedload and sand; this is because the movement of material as bedload is often responsible for problems associated with shifting channels, causing loss of reservoir capacity and other problems, affecting water abstraction, flooding, loss of agricultural land and navigation (Reid *et al.* 1985); (4) bedload material is an important component of ancient geomorphological cycles because a significant proportion of the stratigraphic record consists of fluvial sandstones containing clasts coarser than 0.5 mm in diameter (Meade *et al.* 1990), hence knowledge of bedload processes is important in geological studies; and (5) rivers, such as in Turkey, produce complex deposits containing clasts of diverse lithologies, which relate to the provenance of the sediment (Atalay 1978; Derman 1999). But selective transport effects such as those described in this study may mean that some rock types are under- or over-represented in such fluvial deposits, thus potentially giving a false impression of the catchment.

Research over the last two decades has demonstrated the complexity of factors influencing the nature and rates of coarse-grained bedload transport in river channels. Much of this complexity stems from the mixed-sized nature of the bed material in most coarse-grained channels (Wiberg & Smith 1987) and from the varying bed roughness and structures that are involved (Carling *et al.* 1992), the presence or absence and development and breakdown of bed armouring (Gomez 1983; Andrews & Smith 1992) and whether part or the whole of the bed is in motion. Much attention has been given to the pattern of entrainment in relation to clast size, orientation and degree of protrusion above the bed surface (e.g., Sneed & Folk 1958; Carling 1983; Fenton & Abbott 1977; Ashworth & Ferguson 1989; Hassan & Church 1990; Kirchner *et al.* 1990; Carling *et al.* 1992), but comparatively little attention has been given to particle shape. Results from some studies have suggested considerable variation as to the relative ease of entrainment and speed of transport of clasts of different shapes. Helley (1969) found that equant particles were preferentially transported compared to other shapes, while Krumbein (1942) stressed that, once in motion, elongated particles tend to be transported more rapidly than the equant ones. Meland & Norrman (1966), however, found a poor correlation between shape and transport velocity of clasts in contact with the bed, and Bradley *et al.* (1972) indicated that the order of decreasing mobility was: discs, rollers and spheroids. In contrast, Komar & Li (1986) and Ashworth & Ferguson (1989) found that travel distance increased with sphericity. Detailed field experiments using tracers on the Lainbach in Germany (Gintz & Schmidt 1991; Schmidt & Ergenzinger 1992; Schmidt & Gintz 1995) found, however, that elongated pebbles (notably rods) had the longest mean transport distance (though not statistically significantly longer than those of ellipsoids and spheres), with all three shapes travelling significantly farther than discs, which remained close to their starting points. They linked the relative immobility of discs to their small stoss areas (upstream side of a clast) when lying flat on beds. They found that discs, however, had a transport advantage in large floods. By carrying out a series of laboratory flume experiments, Carling *et al.* (1992) found that the relative mobility of different shapes varies with bed roughness (relative to clast size), with rollers (spheres and rods) favoured on smooth beds, but that on rough beds movement was a little more irreqular with fluctuation in velocity as the clasts passed over underlying pockets, while discs could bridge gaps more easily.

A probable cause of differing results, and of problems comparing between studies, comes from the different approaches adopted. Many flume-based studies and painted-clast experiments involve monitoring and comparing the movements of clasts of differing shape and size placed artificially within or upon beds within which they would not be found in nature. In contrast, studies examining (via bedload traps) movement of natural bedload are recording movement of clasts that are set within beds which are themselves the outcome of previous fluvial transport and deposition; thus, differences in entrainment and depositional thresholds and the speeds of movement of bed clasts of differing shape may already be reflected in the bed composition. The populations and boundary conditions of clasts being monitored are thus fundamentally different and pose difficulties regarding meaningful interpretation and comparison. There is a need for more empirical information from a variety of natural bedload situations to help guide the design of future flume experimentation, in particular as regards how transported bedload shape varies with size of flood.

This paper investigates how clast shape of transported bedload varied during a range of winter storm events in the Cwm Treweryn catchment in south Wales. The study focused primarily on the movement of natural bed material as indicated by the catches of bedload traps, though it also reports the results of ancillary experiments using introduced painted clasts. Specifically, the study sought to establish (a) whether the shape composition of trapped bedload varies with size of storm event, (b) whether the shape composition of the bedload exhibits selective transport when compared to available bed material, and (c) whether the nature of shape selectivity varies with size of clast and size of event. It was a limited-scope study designed as a pilot for more detailed research elsewhere (Demir 2000) and should be viewed in that light.

The Study Catchment

The Cwm Treweryn catchment (Figure 1) is located on the northern slopes of the Brecon Beacons in south Wales (51°53’–51°57’ N and 3°34’–3°36’ W). The Cwm Treweryn is about 7 km in length and its catchment covers an area of 10.55 km^2. It is a tributary of the Senni, which flows into the River Usk. Altitude ranges from 550 m in the southeast to 200 m at the gauging station close to the confluence with the Senni. Rainfall and river stage were recorded at Tredustan Hall by the late Dr Derek Maling from 1979 to 1997. The solid geology of the catchment is entirely characterised by the Old Red Sandstone of Devonian age (Barclay *et al.* 1988). Therefore the river bed material consists of sandstone pebbles and cobbles forming a framework, the interstices of which are filled by a matrix of finer sediments. The lithology exerts a strong basic control over bed material clast shape, tending to produce tabular, flat clasts. As a result, larger clasts tend to be dominated by discs and blades of rather blocky form. Smaller (<64 mm b-axis) clasts (produced by breakage) tend to comprise a more even array of spheres, discs, rods and blades, but again many are blocky in nature (high c/b ratios). The solid geology is covered by Upper Pleistocene till, some of which shows evidence of solifluction. Peat is widespread in the upper part of the catchment. Both the till and peat have been deeply gullied by the Cwm Treweryn tributaries (Figure 1). The longitudinal profile of the Cwm Treweryn is concave with an average gradient of 2°. No dams have been built upstream of the study reach so it approximates its natural state. Mean annual rainfall ranges from 1575 mm at Tredustan Hall (1979–1992 average) to 1880 mm at Cray (1916–1950 average), and around 2000 mm at the southern boundary of the catchment. There is a distinct autumn/early winter precipitation maximum, with monthly means at

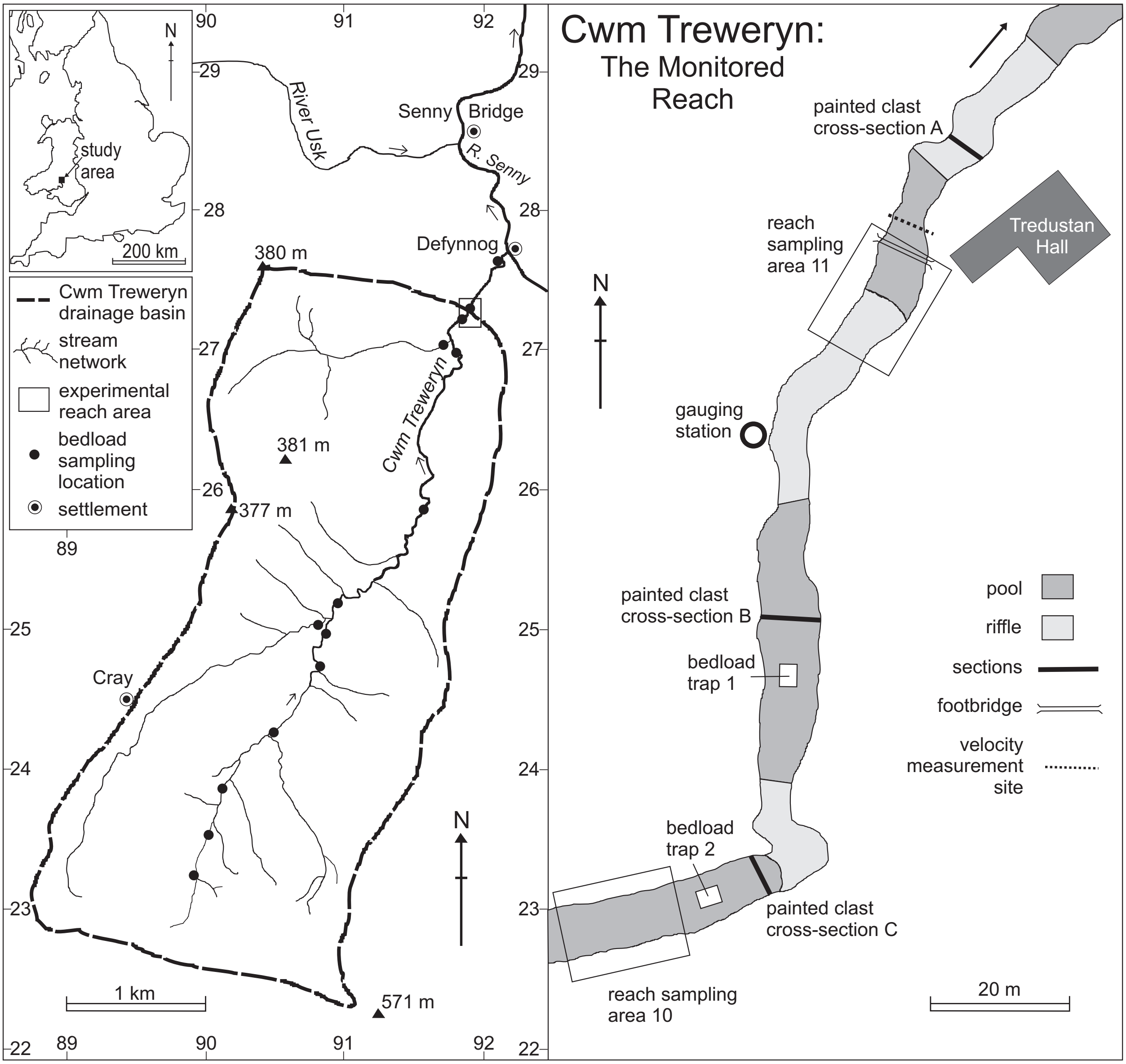

Figure 1. The Cwm catchment (a) and the monitoring reach (b).

Tredustan Hall exceeding 175 mm in November, December and January. Heavy daily falls are rather frequent by British standards, with ≥ 25 mm and ≥ 50 mm occurring 11.1 and 1.2 times (respectively) per annum in 1981–1992. The highest recorded daily fall during the period of record was 94.7 mm on 22 March 1981. Soils are predominantly poorly drained peaty gleys, especially in the headwaters region, but well-drained brown earths of reddish-brown colour occur on the steeper valley-side slopes. The land use is mostly rough unimproved pasture, with some improved pasture on the lower slopes of the lower valley. Less than 5% of the catchment is forested.

Research Design and Methods

The research design comprised the measurement of river flow and bedload movement, clast size and clast shape over the period November 1994 to July 1995 and comparisons with the character of resident bed material in the lower reach of the catchment (Figure 1). River stage was recorded using a British Rototherm pressure-bulb continuous stage recorder. Stage records were converted to discharge values using a stage-discharge rating curve (Figure 2). This curve was based on current meter measurements of discharge at stages of 0.31 to 0.60 m, supplemented by estimates of discharge using the slope-area method for the higher range of stages. Rainfall was recorded at Tredustan Hall using a natural siphon autographic gauge and a storage gauge. The autographic gauge was used to measure rainfall amount, and consists of a funnel and storage system shielded from the free air to prevent evaporation. It also has a pen and chart changed at 09.00 hours GMT. The pen records on the rotating chart and is connected to a float in a precipitation-collecting chamber.

Transported bedload was sampled weekly using two traps of a mesh-basket type over the period from January 1995 to July 1995. The size of each trap was 60 cm wide, 45 cm deep and 20 cm in height; the mesh size was 9 mm. The traps, which were fixed to the channel bed using iron rods, were located at two points 85 m and 35 m above the river gauging station within cross-sections about 9 m in width (Figure 1). Each week, bedload trapped by these samplers was removed, dried and analysed for weight, clast size and clast shape (form, roundness, sphericity and flatness). Bedload size analyses were carried out using direct and indirect measurement techniques. The material from each trap was sieved to separate clasts and particles with a b-axis < 32 mm from the coarser fractions and to determine the amount of material in the smaller size classes of the Wentworth classification. The size distribution was not truncated to the 9 mm mesh size. The full size range analysed varies from < 0.25 mm to > 128 mm. The a, b and c axes of all clasts of at least 32 mm b-axis length were determined using a shape box (Shakesby 1979) and their weights were also recorded. The shape of each clast was categorised into sphere, rod, disc and blade using the Zingg classification (Zingg 1935; Briggs 1977). Krumbein's Sphericity Index (Krumbein 1941) and Cailleux's Flatness Index (Cailleux 1947) were also calculated. For analytical purposes, clasts were grouped into three size categories (32–64, 64–128 and > 128 mm b-axis). The resident bed material was sampled according to the procedure outlined by Wolman (1954). The shape and size characteristics of the resident bed material were assessed using the same methods as described above for a random sample of 300 clasts (200 and 100 clasts, respectively, at two locations) taken from the surface bed material in the reach.

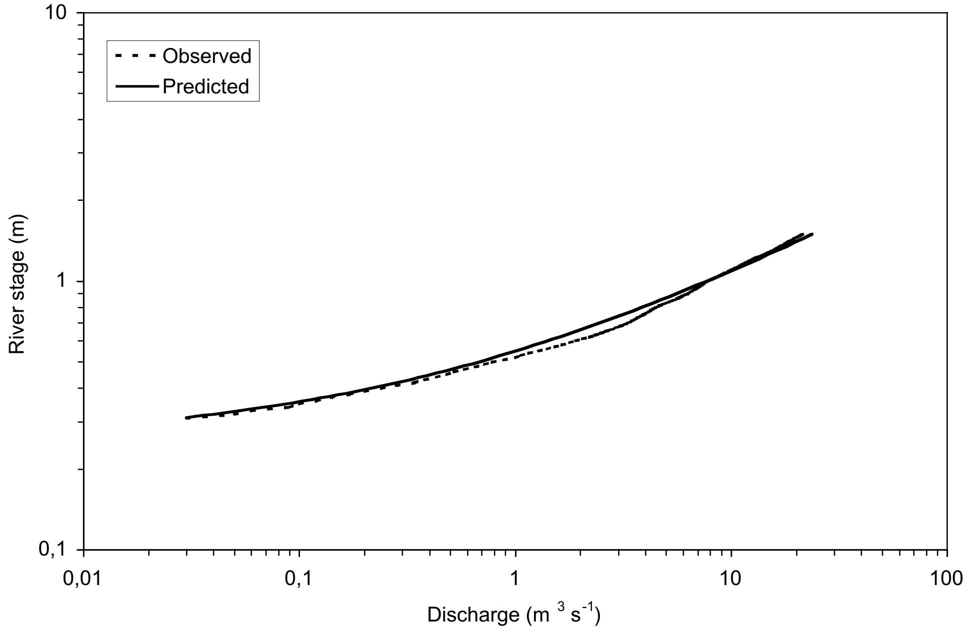

Figure 2. The stage-discharge rating curve for the Cwm Treweryn stream.

In order to give some indication of the nature and scale of clast transport, movements of painted stones of contrasting size and shape from three cross-sections in the study reach were also monitored in a limited painted-stone experiment. However, due to their limited number results of these experiments should be interpreted with caution. Studies which have considered such factors indicated that the number of tracers required to represent reliably the distribution of movement, amounts should be greater than 1000 (e.g., Hassan *et al.* 1991; Ferguson 1992). At each cross- section, 12 painted clasts (one blade, one rod, one sphere and one disc of each of three size categories: "small" < 1000 g; "medium" 1000-1999 g; "large" > 2000 g) were inserted on the stream bed. These weight classes were roughly equivalent to b-axis lengths of < 90 mm, 90–125 mm and > 125, mm respectively. Cross-section A was a pool section, and cross-sections B and C were riffle locations (Figure 1). The clasts were placed at regular intervals 0.4–0.6 m apart but locations closer than 1 m to each bank were avoided. All clasts were placed on 11 January 1995. The river channel was searched after each storm event to determine their new positions and distance of travel. In addition, repeat photography was used to assess clast movements at these cross-sections (both downstream moves of existing clasts and inward movements of clasts from upstream).

Results

Rainfall and River Flow during the Monitoring Period

Rainfall during the months December 1994 to February 1995 was well above average (Table 1), totalling 852 mm compared with an average of 445 mm for 1981–1992 at Tredustan Hall. Daily totals exceeding 15 mm were recorded on thirteen occasions during the period (Figure 3), with seven exceeding 25 mm and a highest fall of 32.5 mm on 18 January 1995. In contrast, rainfall from the second half of March to July was below average. River flow during the period reflected this pattern of rainfall. During the period of bedload assessment from 11 January to 15 July 1995, hydrograph peaks exceeding 5 $m^3 s^{-1}$ were recorded on thirteen occasions, seven of which were > 10 $m^3 s^{-1}$ and three > 15 $m^3 s^{-1}$ (Figure 3). The highest recorded peaks were 19.5 $m^3 s^{-1}$ on 20 January and 17.9 $m^3 s^{-1}$ during the night of 17–18 February. The river was just 0.15 m below bankfull (with a maximum depth of 1.7 m at the gauging station) at the time of the highest recorded flow. The wide range of competent flows covered by the study (around 2.5 to 19.5 $m^3 s^{-1}$; maximum stream depths 0.9 to 1.7 m) permit variations in the amount, size and shape composition of bedload with peak flow to be explored. Table 2 summarises the durations for which stream discharge exceeded different thresholds during the seven weeks in which bedload movement was recorded.

Bedload Movement: Evidence from the Basket Traps

Bedload movement was confined to the period prior to 8 March 1995. The weekly catches of the baskets, broken down into clast-size category, are detailed in Table 2. The bedload trapped by the two baskets has been combined for the purpose of this analysis, because the individual traps caught too few clasts of each shape to be suitable for a reasonable analysis. The combined total was 304.2 kg over the eight-week period 11 January – 8 March, with 99.6 kg at Trap 1 and 207.1 kg at Trap 2. Of this load, clasts with a b-axis of at least 32 mm accounted for 204.1 kg (with 73.7 kg at Trap 1 and 130.4 kg at Trap 2). Clasts trapped in the baskets were restricted to those > 9 mm by the mesh size, although smaller material was occasionally retained. Bedload in individual weeks varied from 4.4 kg in Week 8 to 99.8 kg in Week 6. There was no bedload movement in the week 1 – 8 March (excluded from the table), in which flows were below the threshold for bedload movement.

Transport of all size fractions tended to increase with peak flow and the number of hours with discharge exceeding 10 $m^3 s^{-1}$, but in both cases the relationships showed scatter. Although no clasts greater than 128 mm b-axis in size were transported in Weeks 1 and 8 (in

Table 1. Comparison of rainfall averages for the years 1979–1992 with rainfall during the monitoring period (1994–1945) at Tredustan Hall. All data are in millimetres.

	January	February	March	April	May	June	July	August	September	October	November	December
Mean 1979–1992	185	82	169	90	97	68	67	138	138	160	171	194
1995 or 1994*	301	217	56	42	73	12	47	–	–	–	63*	334*
Anomaly	+ 116	+ 135	-113	-48	-24	-56	-20	–	–	–	-108	+ 140

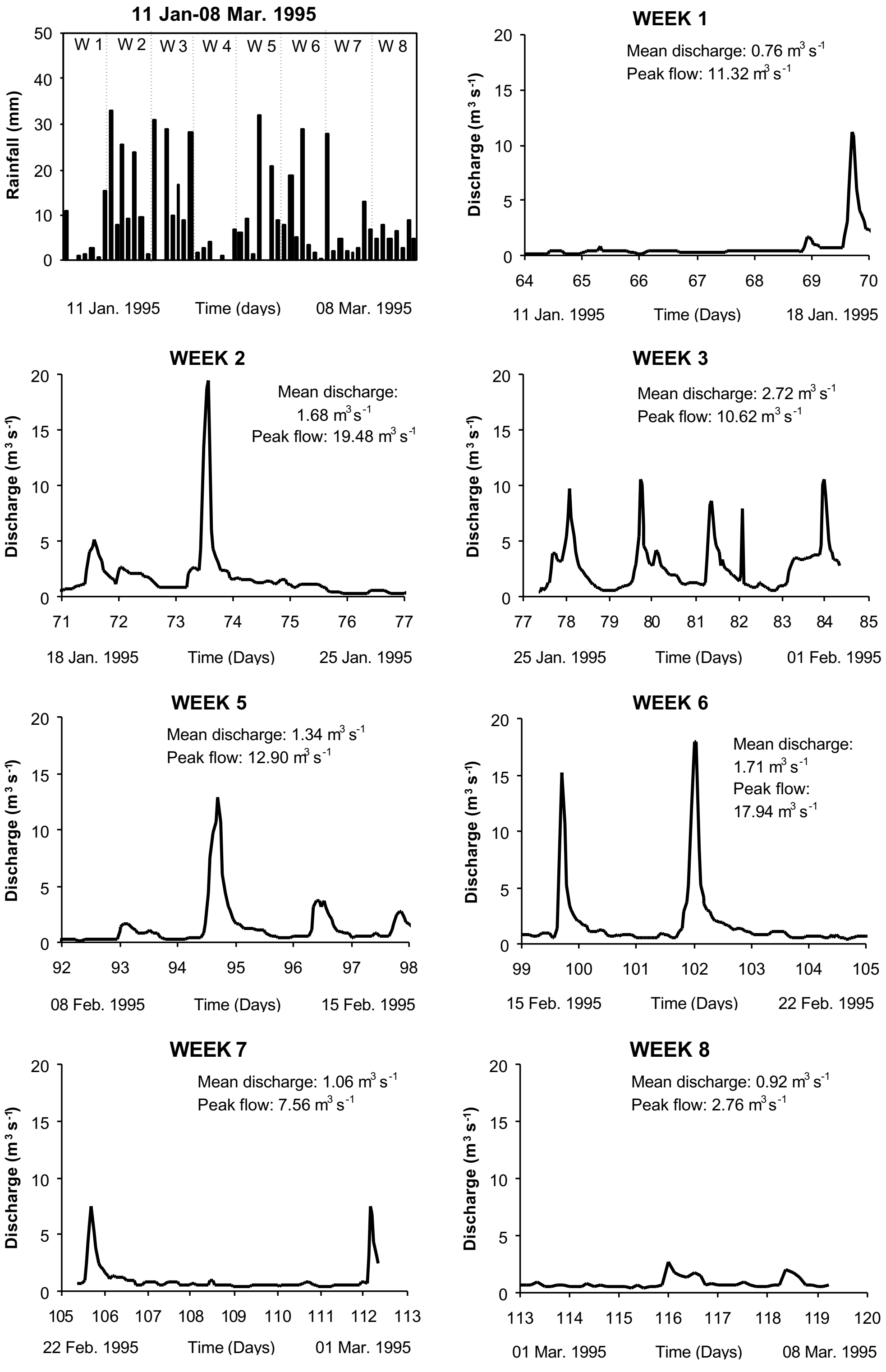

Figure 3. Rainfall and river flow during the monitoring period. Flow for week 4 is not shown as it was too low to cause any bedload movement. The two dates below each graph mark the beginning and end of individual bedload monitoring period (week). The day numbering was started from the day when the river stage and discharge were first monitored (9 November 1994).

Table 2. River flow statistics and bedload by size category for the Cwm Treweryn in early 1995. Results represent two traps together. The approximate maximum capacity of each trap is 75 kg in weight and none of the week they reached their capacity during the monitoring period.

Week	Dates	Mean Flow (m^3 s^{-1})	Peak Flow	Hours with flow (m^3 s^{-1})			Bedload (kg/week)				
				5	10	15	< 32 mm	32–33 mm	64–127 mm	>128 mm	Total
1	11–18 January	0.76	11.32	4	2	0	2.81	3.30	6.01	–	12.12
2	18–25 January	1.68	19.48	5	3	2	24.59	21.61	25.46	7.06	78.72
3	25 January – 1 February	2.72	10.62	18	4	0	17.35	17.05	12.92	2.02	49.35
4	1–8 February	0.68	2.49	0	0	0	–	–	–	–	–
5	8–15 February	1.34	12.90	6	3	0	14.34	7.44	11.18	2.56	35.52
6	15–22 February	1.71	17.94	10	5	3	37.10	20.76	31.48	10.46	99.77
7	22 February – 1 March	1.06	7.56	5	0	0	6.22	6.14	11.40	3.11	26.86
8	1–8 March	0.92	2.76	0	0	0	0.22	0.65	3.52	0.00	4.39

which peak flows reached just 11.32 and 2.76 m^3 s^{-1} respectively), the proportions of the total load accounted for by the other three size fractions did not vary systematically with peak flow or other flow variables (Table 2). The only exception was the anomalously low percentage (5.0 %) accounted for by small material (< 32 mm b-axis) during the week of lowest peak flow (Week 8), whereas such small material provided 23.2–40.4 % of the total load in the other six weeks with bedload movement.

Shape of Transported Bedload Clasts Compared with Resident Bed Material

The shape and b-axis size characteristics of the randomly sampled bed material from the monitored reach are summarised in Table 3, which compares the shape of transported clasts and reach bed material by size category for the entire monitoring period. In the 32–64 mm size class, discs and – to a lesser extent – spheres were over-represented, and blades and particularly rods were under-represented in the trapped material. Although discs were again over-represented in the 64–128 mm category (57.7 % compared with 46.6 %), the differences are much less than for the smaller size material. All but one of the 14 >128 mm b-axis clasts that were moved were discs and spheres, with blades (27.9 % of the large bed material clasts) particularly under-represented. Simple classification, however, into spheres, rods, discs and blades is rather limiting, taking no account of angularity/roundness, which can profoundly affect entrainment and transport. Figure 5

Table 3. Distribution of shapes of trapped bedload clasts compared with sampled reach bed material by size category.

Clast size category	Clast shape (% frequency)				Number of clasts
	Spheres	Blades	Rods	Discs	
32–64 mm					
Transported	33.7	15.7	15.3	35.3	632
Reach	28.1	21.9	32.8	17.2	64
T–R	+ 5.6	-6.2	-17.5	+ 18.1	
64–128 mm					
Transported	19.0	14.3	9.0	57.7	189
Reach	18.7	21.2	13.5	46.6	193
T–R	+ 0.37	-6.7	-4.5	+ 11.1	
> 128 mm					
Transported	28.6	0.0	7.1	64.3	14
Reach	9.3	27.9	2.3	60.5	43
T–R	+ 19.3	-27.9	+ 4.8	+ 3.8	

shows Zingg diagrams of the shapes of all transported clasts for each week with bedload movement during the monitoring period. It can be seen that none of the clasts were "true" spheres, rods, discs or blades (which would plot in the extreme corners of the Zingg diagrams). This applied to both the trapped and resident bed material (Figures 4 & 5). Thus most of the rods and blades were 'marginal' and characterised by high b/a axis ratios (> 0.4), tending towards spheres and discs, respectively. Likewise, many of the discs had high c/b axis ratios and were marginal to spheres. Many of the spheres and discs were blocky and angular in nature. As mentioned previously, these characteristics are strongly linked to the Old Red Sandstone lithology, which tends to produce tabular clasts, which then break into blocks.

Variations in the shape of trapped bedload clasts between individual weeks during the monitoring period are shown in Figure 6. Relationships of frequency of different shapes to peak flow during these periods are depicted in Figure 7. Again, each size category is analysed separately. For the small (32–64 mm) category, discs were of greater relative importance in weeks with lower peak flows (Weeks 3, 7 and 8), but were exceeded in frequency by spheres in the two weeks with highest peak flows (Weeks 2 and 6). Blades were of very low percentage frequency (< 5%) or absent in the two weeks in which peak flows were less than 10 m^3 s^{-1}, but exceeded 20% in two of the three intermediate peak flow weeks. Rods accounted for 27% of clasts in Week 7, but otherwise ranged unsystematically in relation to peak flow. For the 64–128 mm category, spheres were of greater relative importance (25–27% of clasts) in the two highest events than in the five others (10–17%). Blades were of greatest relative frequency at medium flows (23–30%), but were absent in the lowest peak flow event and of low frequency (< 10%) in the highest peak flow weeks. Rods were unrecorded in three weeks but overall showed no clear relationship to peak flow. As with smaller size clasts, the frequency of discs declined with peak flow from over 80% in Week 8 to 50–55% in the two weeks with highest flows. There were too few clasts in the >128 mm category for meaningful variations to be assessed.

Table 4 summarises roundness, sphericity and flatness characteristics of the transported clasts during the monitoring period and compares values with those obtained for the sampled bed material in the reach. For both size categories, differences in mean roundness, sphericity and flatness both of the trapped clasts from week to week and between transported and resident reach material were minor. Transported clasts were somewhat rounder, more spherical and less flat than the reach material.

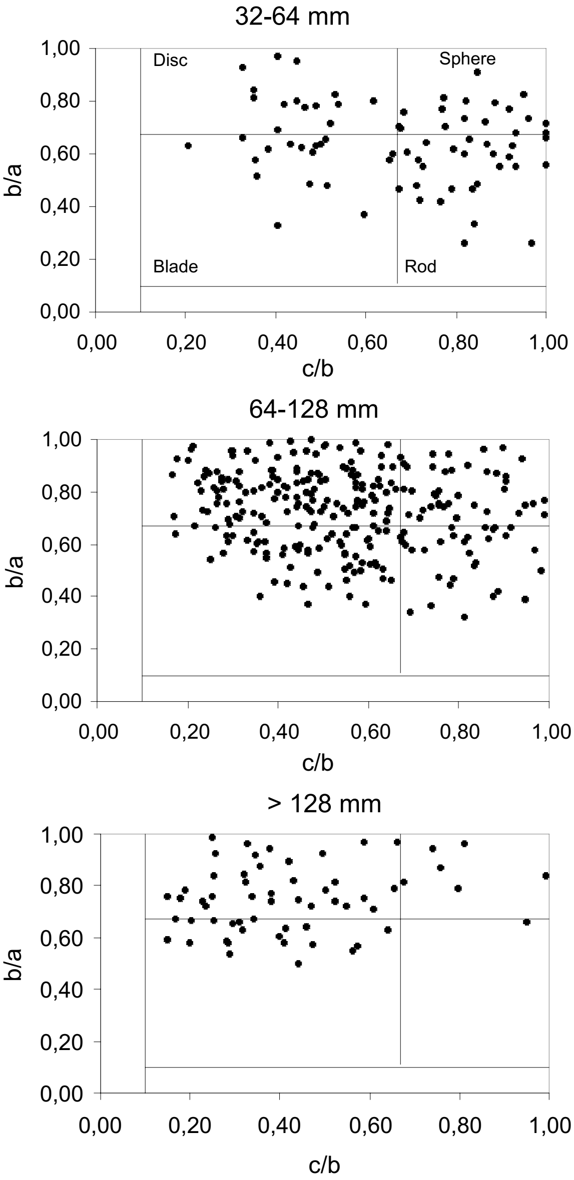

Figure 4. Zingg diagrams of the shape of resident material clasts in the b-axis size classes 32–64 mm, 64–128 mm and > 128 mm respectively.

Additional Evidence from the Painted-Clast Experiments

Table 5 gives details of the movements on the stream-bed at cross-sections A, B and C of the 35 painted clasts (of

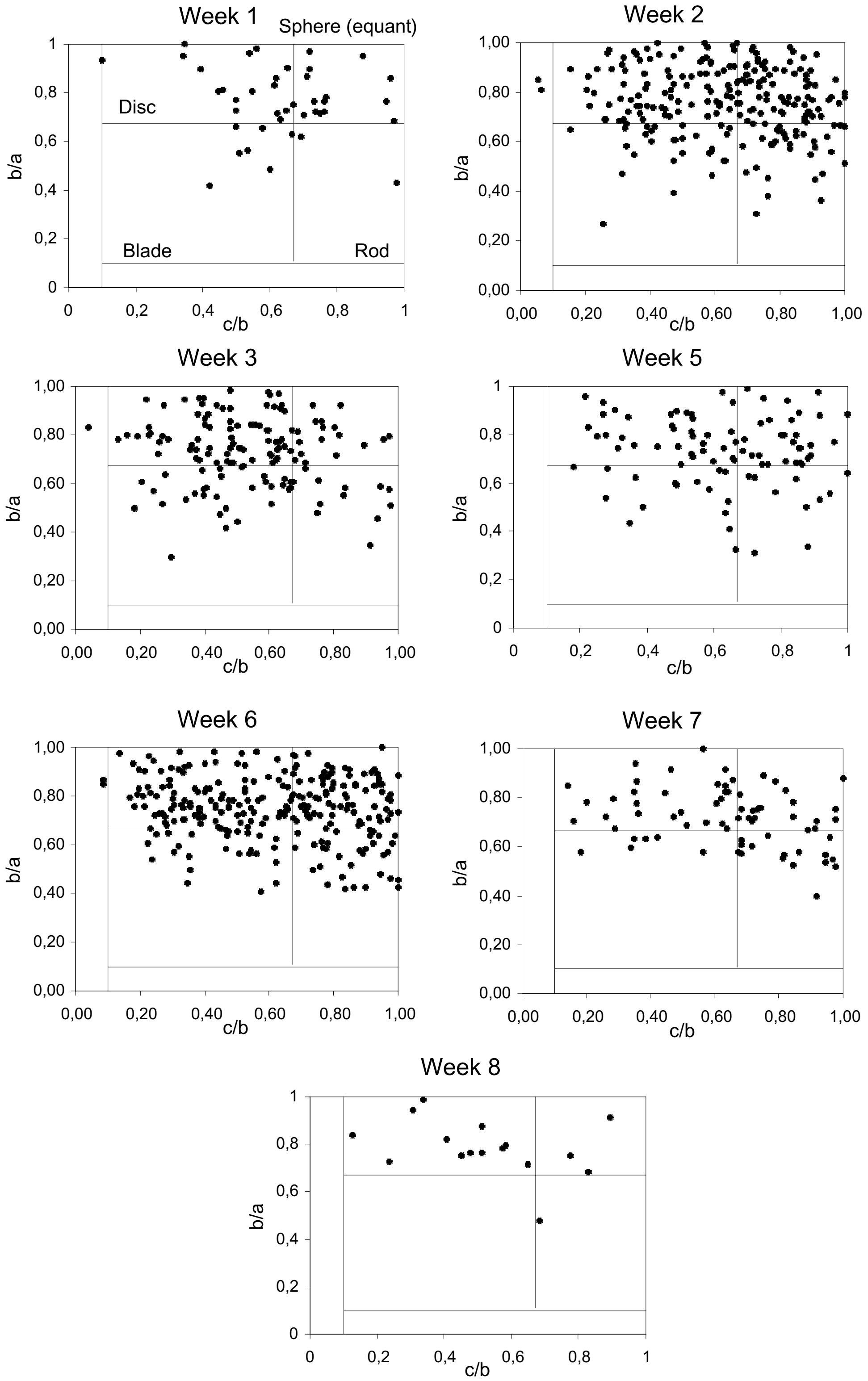

Figure 5. Zingg diagrams of the shape of transported clasts (all size classes combined) for each week during the monitoring period.

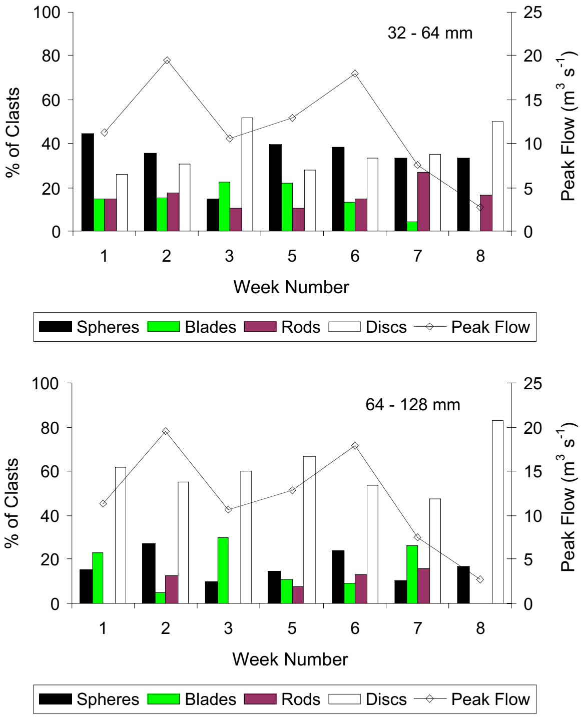

Figure 6. Variations in the shape of trapped bedload clasts between individual weeks in the monitoring period.

contrasting shape and weight) from the date of insertion on 11 January 1995 to 15 March 1995 (after which no further bed movement was recorded). Of the 35 clasts, 25 (all of which moved) were traced throughout the period and 10 disappeared (either buried or moved out of the reach) during the period. Eight of these ten had measured movements prior to their time of disappearance and were included in the calculations of means. Re-detection of clasts was 100% for cross-section A (the pool section), but 25% and 58% of clasts disappeared at the two riffle cross-sections. The longest distances of travel (100.0–104.0 m) were recorded by a medium sphere, a large sphere and a small rod (all of which had been inserted at the pool location of cross-section A); in addition, a small sphere moved 62.8 m before it disappeared in a succeeding flood, and a small blade and two of the small discs also moved over 50 m. Both medium and large discs moved on average much shorter distances (4.2/2.5 m) than rods (7.7+ / 10.3+ m) and particularly spheres (51.0 / 35.0+ m) of corresponding size. Most movement occurred in the two weeks (Weeks 2 and 6) containing the three largest storm events of 21 January (19.5 m^3 s^{-1}), 16 February (15 5 m^3 s^{-1}) and 18 February (17.9 5 m^3 s^{-1}). Sixteen of the 34 remaining clasts moved during the 21 January event, with six moving distances of 14 to 62 metres. In the period containing the mid-February events, five clasts disappeared and seven moved distances of 12 to 90 metres.

Discussion

Bedload Size Composition and Discharge

Notwithstanding the limited scope of the experiments, the lack of variation in size composition with increasing peak discharge and the fact that the ratio of cobble to gravel fraction by weight was highest (5.42) in Week 8, in which peak flow (2.76 m^3 s^{-1}) and bedload were low (Table 2), indicate a bedload regime in the Cwm in which

Table 4. Means of roundness, sphericity and flatness of trapped bedload clasts compared with sampled reach bed material by size category. Weeks are as in Table 2.

Week	Peak Flow	Sample sizes (clasts)		Roundness		Sphericity		Flatness	
	M^3 s^{-1}	32–64 mm	64–128 mm	32–64 mm	64–128 mm	32–64 mm	64–128 mm	32–64 mm	64–28 mm
1	11.32	27	13	202	208	0.71	0.73	184	210
2	19.48	181	40	225	167	0.69	0.69	230	267
3	10.62	106	30	217	141	0.68	0.65	217	331
5	12.90	68	27	203	178	0.67	0.65	212	264
6	17.94	196	54	216	176	0.69	0.70	115	252
7	7.56	48	19	258	240	0.69	0.67	213	234
8	2.76	6	6	234	175	0.68	0.68	221	298
Overall	n/a	632	189	222	184	0.69	0.68	199	265
Reach material	n/a	64	193	191	153	0.64	0.65	218	254

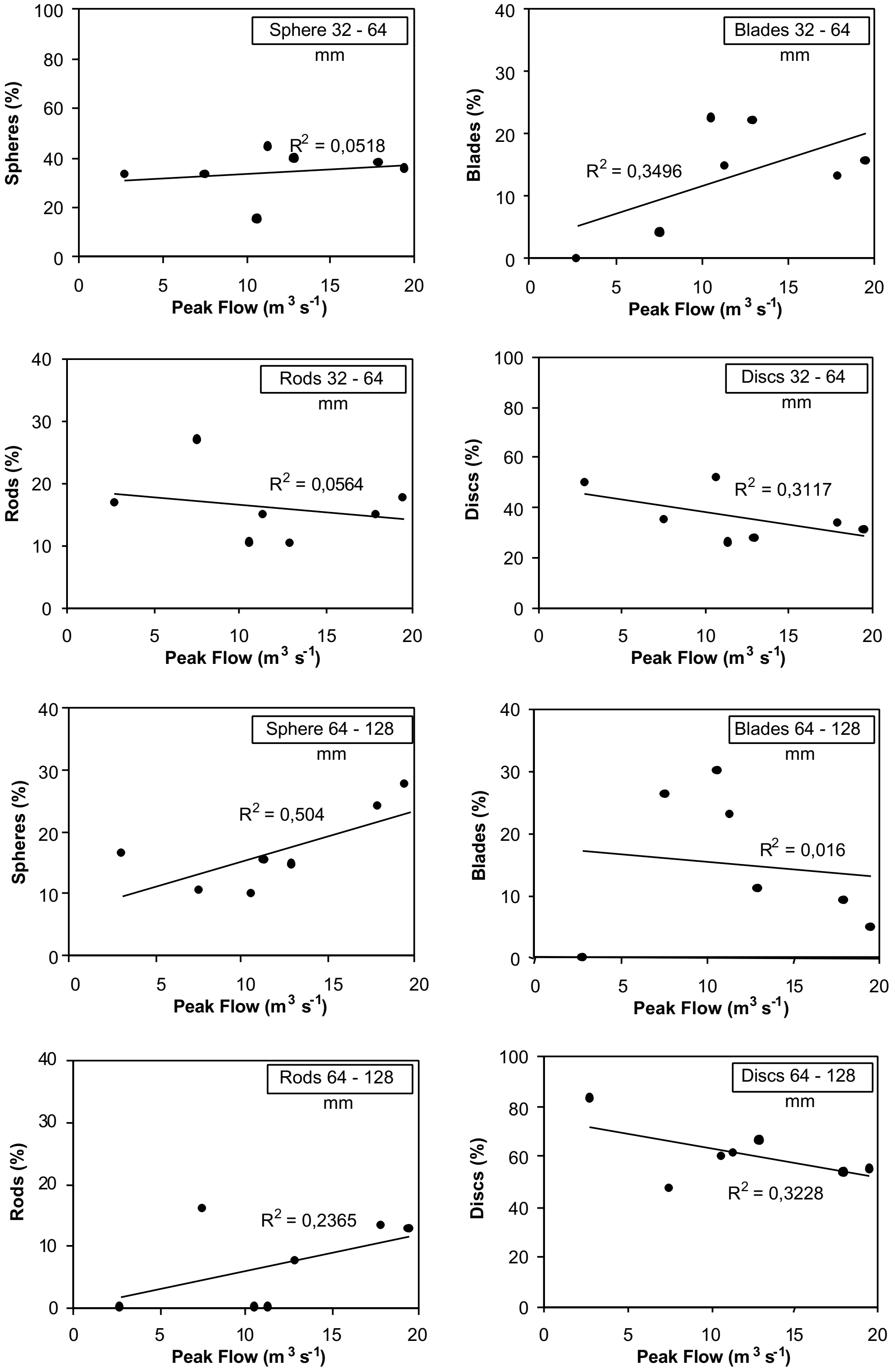

Figure 7. Relationships of percentage frequency of clast shape to peak flow during individual weeks in the monitoring period.

Table 5. Summary of distances travelled (m) by painted clasts of different shape and size during individual weeks and the entire monitoring period (11 January to 15 March 1995). Clast size categories were as follows: small = < 1000 g weight; medium = 1000–1999 g weight; large = > 2000 g weight. D indicates the clast disappeared. Values in brackets indicate distances travelled before time of disappearance.

CLAST SHAPE	DISTANCE TRAVELLED BY CLASTS (metres)					
	SMALL CLASTS		MEDIUM CLASTS		LARGE CLASTS	
	Individuals	Mean	Individuals	Mean	Individuals	Mean
Spheres	1.2; 0.2; (62.8+D)	21.4 +	100.0; 2.0; D	51.0	104.0; (0.5+D); (0.5+D)	35.0 +
Blades	50.2; 0.6; D	25.4	7.0; (4.0+D) (4.3+D);	5.1 +	3.0; 0.9	2.0
Rods	101.9;26.0; 3.0	43.6	5.2; (14.0+D); (4.0+D)	7.7 +	21.0; 6.8; (3.1+D)	10.3 +
Discs	1.5; 62.2; 56;4	40.0	6.0; 6.0; 0.5	4.2	3.0; 0.1; 4.3	2.5

significant movement does not occur until the dominant cobble-sized material is mobilized. Indeed, the cobble bed material resembles a protective armour (Gomez 1983) in the monitored reach, suggesting that entrainment of a clast is dependent on other clasts that form the bed structure. Thus, entrainment of small-sized clasts in an armoured bed is assumed to be more difficult due to a hiding effect of larger bed roughness elements. The confinement of transport of larger (> 128 mm b axis) cobbles to weeks with the highest flows, however, demonstrates that any '*hiding effect*' tendency is probably confined to clasts of dominant size (small cobbles) and smaller. Also, although in weight terms more cobble-sized than gravel material was trapped, the frequency of 32–64 mm compared with 64–128 mm clasts was much higher in the trapped material (632 compared with 189) than in the randomly sampled surface reach material (64 compared with 193) (Table 3). Both of these features tend to indicate a degree of size selection, as found in other coarse bedload studies (Ashworth & Ferguson 1989; Komar & Shih 1992). On the other hand, it may merely indicate surface armouring in the reach material and a resultant bias towards larger clasts in the surface-sampling strategy of reach material that was used in the study. Another possibility is that smaller clasts may be transported, on average, greater distances than larger clasts leading to their greater representation in the trapped bedload (cf. Church & Hassan 1992). The dominance of cobbles at the most marginal bedload transport conditions is interesting; it may point to an absence of finer material amongst the perhaps looser and more projecting cobble clasts that may be the first to be entrained.

Shape of Trapped Bedload Clasts Compared with Resident Reach Material over the Monitoring Period as a Whole

Shape composition and variation between size fractions is substantially controlled by lithology; the Old Red Sandstone produces large tabular slabs, which results in the dominance of flat (albeit somewhat blocky) cobbles (Table 3). Clasts in the large gravel fraction, however, are the result of fracture of larger tabular material, the outcome of which is a more even spread of shapes in the reach material (Table 3). Amongst the large gravel (32–64 mm b-axis) fraction, discs (and to a lesser extent spheres) were over-represented and rods (and to a lesser extent blades) were under-represented in the trapped material compared with the upstream reach material (Table 3). Similar, but less marked tendencies were evident in the small cobble (64–128 mm) category, though spheres were in this case not over-represented. Transported clasts were somewhat more rounded, but only marginally more spherical than the reach material (Table 4).

There are three possible reasons for differences in shape between trapped and resident bed material: (1) clasts of some shapes are selectively entrained; (2) clasts of some shapes, once entrained, travel faster and/or faster and thus are trapped more frequently; (3) the sampled surface bed material is not truly representative of transported bed material as a whole because of possible differences in shape with depth within the mobile bed material. At first glance, the over-representation of discs would appear to be at variance both with the findings of previous studies (e.g., Schmidt & Gintz 1995) and with the results of the (admittedly limited) painted-clast experiment, in which discs moved much shorter distances than rods and spheres. There may be two reasons contributing to the over-representation of discs. First, clasts have been categorised on the basis of their b-axis, but flat clasts (discs and blades) are significantly lower in weight than spheres and rods of similar b-axis dimensions (Lane & Carlson 1954) and are arguably more easily entrained and transported. Secondly, bedload transport in the Cwm may resemble a *'rough bed'* rather than a *'smooth bed'* environment. Whereas in smooth bed conditions spheres tend to roll easily and are preferentially transported (Krumbein 1942; Meland & Norrman 1966), on very rough beds spheres move slowly relative to flatter clasts (Meland & Norrman 1966; Bradley *et al.* 1972; Johansson 1976; Steidtmann 1982; Carling *et al.* 1992). Whereas smooth beds favour rollers (spheres and rods), rough beds favour the movement of flatter clasts (discs and blades), which span gaps between clasts more effectively and are lifted and move by sliding, with spheres tending to lodge in the gaps between the clasts or follow longer, meandering paths around obstacles (Carling *et al.* 1992). Along with their somewhat blocky shape, this may explain why spheres are not as over-represented as discs in the large gravel and small cobble categories. On the other hand, the tendency for spheres to be greatly over-represented in the largest (large cobble) clast size category (Table 3) may paradoxically reflect that the bed is *'smooth'* rather than *'rough'* with respect to such large clasts, as the latter, even if spherical in shape, are sufficiently large to bridge gaps between the dominant small cobble material.

Both of these explanations of the over-representation of discs in the large gravel and small cobble categories could reflect a differential in speed of movement between flatter and spherical shapes rather than their preferential entrainment, as the clast-size evidence (see above) suggests an equal mobility regime of transport. An additional complicating factor that may be affecting bedload transport is that most of the bed clasts deviate considerably from the *'ideal'* shape types (Figures 4 & 5) and hence may not conform to model sphere, disc, blade and rod entrainment and transport behaviour. In particular, the roundness/angularity characteristics have a profound influence. So-called spheres and rods can be highly angular; cubes = spheres in the Zingg classification used here, although the term 'equant' is perhaps better (Helley 1969).

Variations in Bedload Shape with Discharge

Figure 7 shows variations in flow and the percentage of sphere-, blade-, rod- and disc-shaped clasts of 32–64 and 64–128 mm size in the trapped-transported material. Fitting regression lines indicates the relationships are statistically weak; however, some interesting observations can still be made. For example, if a line is drawn across each of the graphs shown in Figure 7, showing the proportion of clasts of each shape present in the bed, then for the 32–64 mm material, the proportion of spheres caught is about representative across the range of flows. The proportion of blades appears to increase and the proportion of discs decrease toward the limit of proportion in the bed as flow increases. The proportion of rods appears to be under-represented across the range of flows. For the 64–128 mm material, discs behave in approximately the same way, but spheres appear to shift from being under-represented toward being over-represented in the load. Blades behave erratically (but decline sharply if the first observation is ignored), while rods appear to be represented across the range (but with some notable excursions to zero). Therefore, in summary:

1. There is a tendency for the proportion of transport tracer shapes to become more like the bed material as flow becomes stronger and entrainment less selective;
2. Discs are preferentially entrained at lower flows, closer to the threshold for motion;
3. The low flow result (2.76 $m^3 s^{-1}$; 4.4 kg trapped) is misleading and should perhaps be discounted.

Furthermore because the data are in percentage terms, the percentage of clasts is dependent on the behaviour of other clast shapes in the sample. Therefore the apparent behaviour of any shape may be the result of the behaviour of the other shapes. Secondly, the gravel carried by the Cwm Treweryn stream is less uniform in shape, and very little of the natural bed material is in the form of *'true'* spheres, blades, rods and discs. By categorising bed clasts as discrete sphere, blade rod and disc shapes, much information on the precise shapes in the natural bed material is lost. In other words, some of the shapes in the natural bed material may not be represented.

Painted-Clast Evidence

Given the small samples of clasts used and the proportion of disappearances, the results of the painted-clast experiments must be interpreted with caution. The results nevertheless tend to conform to both theoretical considerations and the findings of other bedload tracer studies (e.g., Schmidt & Ergenzinger 1992; Schmidt & Gintz 1995; Warburton & Demir 1998). Thus medium and large blades (and to a lesser extent discs) moved on average much shorter distances than rods and particularly spheres of similar weight (Table 5). Warburton & Demir (1998) also found that sphere- and rod-shaped particles moved farthest, discs less far and blades hardly at all in a field experiment of clast movement using magnetically-tagged particles in a gravel-bed river in north-east England.

Medium and large spheres travelled long distances in the Cwm Treweryn compared to the very short distances travelled by two of the three small spheres. This is in accordance with the experimental findings on sphere transport of Carling *et al.* (1992). They found that spheres travelled faster on smooth than rough beds: larger spheres tend to 'bridge' the gaps between clasts on a heterogeneous bed, whereas spheres that are smaller than the dominant clast size are liable to wedge in the gaps between the larger clasts. Small rods (which present larger stoss ends) and small discs (which are liftable) tend to be more transportable than the more compact small spheres.

The distances moved over the monitoring period and the differences with shape are broadly similar to those recorded by other gravel-bed river studies. Thus Stott & Sawyer (1998), who monitored the movement of large samples of magnetically tagged clasts over periods of up to 2.5 years in two channels in the Plynlimon area of central Wales, found that rods and spheres (295 m a^{-1}) moved on average 7–8 times faster than discs and spheres (40.2 and 43.8 m a^{-1}, respectively). The relatively low speeds of disc movement recorded both by the limited Cwm Treweryn experiment and other studies suggest that over-representation of discs in the trapped bedload may be accounted for by their preferential entrainment rather than greater speed of movement.

Conclusions

The shape composition of bedload clasts captured by basket-traps on the Cwm Treweryn and differences in comparison with upstream reach material varied greatly with clast size and peak discharge. Discs were over-represented in the trapped bedload compared to reach material in all size categories, but the differences decreased with increasing clast size. Rods were under-represented in the large gravel and less so in the small cobbles, but over-represented in the large cobbles. Blades were under-represented in all categories. Spheres were markedly over-represented in the large cobble category.

Variations in flow and the percentage of clasts of differing shapes in all size categories indicated that, overall, the relationships are statistically weak. Two possible reasons were attributed to these weak relations: (1) as the bed material in the Cwm Treweryn resembles protective armour, the apparent behaviour of any shape may be the result of the behaviour of the others; (2) the gravel carried by the Cwm Treweryn stream is less uniform in shape. The increased irregularity of particle shape, such as blocky sphere and rod-like clasts with low roundness, or disc and blade-like clasts with greater c/b ratio, are expected to diminish the influence of shape on hydraulic behaviour. However, some interesting observations from these experiments are that the percentage of spherical large gravel and spherical and rod-shaped small cobble clasts increased with peak discharge, whereas discs of all sizes tended to decline with peak discharge. Blades were over-represented in medium events but not moved in smaller competent events and were under-represented at very high flows.

The lack of variation in the size composition of the bedload (regarding the ratio of small cobble to large gravel material) except at the highest flows, when large cobbles begin to be moved, strongly suggests rough bed conditions and the preferential movement of clasts that span and do not get trapped by roughness elements. This situation favours discs rather than blades, as the latter are rather blocky and angular and are more difficult to entrain. The over-representation of spheres and to a lesser extent rods amongst the largest material (large cobbles), on the other hand, may suggest that – due to the their larger size relative to the underlying bed roughness elements, and their greater sphericity and roundness – they do not get easily trapped by roughness elements and protrude into the flowing water, enabling them to become entrained and move preferentially. The finding from the painted-clast experiments, that larger spheres tended to move farther than smaller ones, tends to support this.

The other principal finding of the painted-clast experiments (as in other studies) is that spheres and rods move greater distances than discs and blades, suggesting that selectivity in entrainment is decisive in accounting for the shape composition of the trapped bedload at low and moderate peak flows.

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