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Importance of clast size and shape on selective bedload transport in a coarse-gravel bed river: Trout Beck, England

İri çakıl yataklı bir akarsu kanalında tane boyut ve şeklinin seçimli yatak yükü taşınmasındaki önemi: Trout Beck Nehri, İngiltere

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ABSTRACT

This paper describes field experiments designed to investigate importance of shape and size of natural clasts in bedload transport in an upland coarse-gravel bed river, the Trout Beck. Transported bedload was trapped twice on different occasion and bed material was sampled at five sections according to the procedure outlined by Wolman. Magnetic tracing experiment was carried out at the same reach to quantify the selective transport of different size and shapes of coarse river gravel and determine their spatial sorting within a natural stream channel. In general, comparison of sampled bed material and trapped bedload showed much stronger size selectivity, and to some extent, shape selectivity. Smal clasts in the trapped bedload were over-represented compared to the residual material. In the trapped bedload sphere and disc-like clasts were over-represented, while blade and rod-like clasts were under-represented. Results of the magnetic tracing experiment also showed evidence of both size and shape selectivity. Preferential movement occurred in the fine clasts (32-64 mm) size classes with tracers located along the channel thalweg moving the greatest distance. In terms of shape, during virtually all survey periods, sphere clasts were transported the greatest distance and greatest in numbers. Rod and, to some extent, discs also moved preferentially but blades moved only short transport distances and less in number.

Key words: Bedload, clast shape, gravel-bed stream, roundness, sphericity, Trout Beck river.

ÖZ

Bu makale Trout Beck akarsuyunda taşınan çakıl ağırlıklı yatak malzemesinin boyut ve şekil özelliklerinin taşınma üzerindeki etkilerini araştırmak amacıyla gerçekleştirilen arazi çalışmalarına dayanmaktadır. Taşınan yatak malzemesi iki farklı zamanda örneklenmiş olup, yatak yükü malzemesi örneklemesi ise Wolman yöntemi uygulanarak beş ayrı yerde yapılmıştır. Doğal bir akarsu yatağında çakılın boyut ve şekil özeliklerine bağlı olarak oluşan seçici taşınma ve çakılların yatak boyunca dagılımının niceliksel olarak belirlenmesi amacıyla mıknatıslı çakıl deneyleri yapılmıştır. Örneklenen yatak malzemesi ve tutulmuş yatak yükü malzemesinin karşılaştırılması sonucunda anılan yerde çakıl boyutuna bağlı olarak belirgin bir seçici taşınma, buna karşılık çakıl şekli itibariyle kısmi bir seçici taşınma söz konusu olduğu anlaşılmıştır. Tutulmuş malzeme içerisindeki küçük boyuttaki çakılların oranı, yatak malzemesindekine göre daha fazladır. Yatak malzemesiyle karşılaştırıldığında, tutulmuş yatak yükü içerisindeki küresel ve prizma benzeri çakılların oranı daha fazla, buna karşılık çubuk (ovalimsi) ve bıçak benzeri yassı çakılların daha az oranda olduğu belirlenmiştir.Mıknatıslı çakıllarla yapılan deney sonuçları ise, hem çakıl boyutuna hem de çakıl şekline bağlı olarak seçici taşınma örneklerini ortaya koymuştur. Küçük boyut kategorisindeki çakıllar (32-64 mm), akarsu yatağı talveğini takiben en uzak mesafeye taşınmışlardır. Şekil özellikleri itibariyle, hemen bütün ölçüm dönemlerinde, küre şekilli çakıllar hem sayıca fazla hem de taşınma mesafesi açısından büyük değerler göstermiştir. Çubuk ve kısmen prizma şekilli çakıllar da seçici taşınma örneği göstermişlerdir; ancak yassı şekilli çakıllar gerek sayı itibariyle, gerekse taşınma mesafeleri itibariyle oldukça düşük değerler sergilemişlerdir.

Anahtar kelimeler: *Yatak yükü, çakıl şekli, çakıl-baskın akarsu, yuvarlaklık, küresellik, Trout Beck nehri.*

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INTRODUCTION

Bedload transport in upland streams and rivers has gained the attention of earth scientists and engineers for many decades. Although there is a considerable body of literature on sediment transport in lowland rivers, less is known about the pattern of sediment transport in coarse-bed upland streams. Studies have shown that there are significant differences between upland and lowland gravel-bed rivers (Simons and Simons, 1987). Bathurst (1987) stressed that bedload transport rates in mountain rivers are higher than those in lowland rivers and the actual mechanisms of bedload transport are poorly understood. Lack of understanding is attributed to difficulties in the field measurement of bedload transport and associated hydraulic conditions in steep, coarse-bed channels (Carling, 1989). Some of these differences are summarised by Newson (1981). He points out several important characteristics of mountain and piedmont streams. For example, mountain streams have steep channels and side slopes without an intervening floodplain. The dominant bed material consists of coarse bedload. Flow resistance is complex and generally controlled by large-scale roughness elements and the local characteristics of the bed material (such as shape, size and density). Under conditions of steady flow there is a wide scatter in the relationship between hydraulic variables and bedload transport in coarse-bed mountain rivers. Several factors have been identified as causing this scatter in the sediment transport relationship. These include sedimentological characteristics of the bed (e.g. microform bed roughness elements) (Jackson and Beschta, 1982; Parker and Klingeman, 1982; Hoey, 1989; Reid et al., 1992), the progressive construction of an armour layer during waning flood flows (Proffit and Sutherland, 1983; Gomez, 1983), variable cementation of the gravel framework by interstitial matrices (Frostick et al., 1984; McEwan, 1999), characteristics of individual moving clasts (e.g. size shape, density, etc.) (Hassan and Church, 1990) and pool-riffle sequences (Robert, 1990).

Although coarse material transport is an important part of many fluvial problems, geomorphologists and engineers have only relatively recently attempted to examine sediment production and transport processes in coarse-bed rivers in upland areas. Transport mechanisms of coarse-bedload in mountain rivers with irregular beds are still relatively poorly understood (Ergenzinger and Custer, 1983).

Understanding of transport mechanisms of coarse-bedload in fluvial geomorphology has grown considerably in the last two decades as a result of improved theoretical comprehension and carefully conducted field and laboratory experiments (Wiberg and Smith, 1987; Ashworth and Ferguson, 1989; Gomez and Church, 1989; Gomez, 1991; Carling et al., 1992; Schmidt and Ergenzinger, 1990). However, these studies have mainly tended to focus on bedload processes: equations to model thresholds of bedload movement and bedload transport rates (Bagnold, 1941, 1980; Wilcock, 1988; Wilcock and Southard, 1989); bedload sampling and measurement methods (Hubbel, 1964; Helley and Smith, 1971; Bathurst, 1987); measures of bedload character such as sorting, etc. (e.g. Wadell, 1932; Cailleux, 1947; Krumbein, 1941a); bedforms and their dynamics such as riffles, pools, bars, etc. Although extensive research has been carried out with regard to different aspects of bedload dynamics, it is rather surprising that the importance of bed material shape in influencing sediment transport in coarse-bed streams has received little attention.

Shape is thought to be significant factor because, all other factors being equal, the entrainment and hydraulic behavior of a clast depends on its shape, orientation and its relative projection above the mean bed level. Several studies, including both field and laboratory experiments, have shown how different particle shapes exert an influence on bedload transport in coarse-bed rivers (e.g. Wentworth, 1919; Krumbein, 1942; Unrug, 1957; Sneed and Folk, 1958; Bradley et al., 1972; Komar and Li, 1986; Schmidt and Ergenzinger, 1992; Carling et al., 1992; Schmidt and Gintz, 1995). Changes in dynamic conditions of transport, are reflected by changes in the shape-sorting, size and packing of deposits. However, despite its importance the exact mechanisms of how shape influences sediment transport are not fully understood and there are some conflicting results from existing studies. It is therefore timely that a systematic study should be directed at improving the understanding of bedload transport mechanisms in terms of clast shape.

Many flume-based studies and painted stone 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 that are themselves the outcome of previous fluvial transport and deposition; thus, differentials 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.

This paper investigates how size and shape composition of the trapped bedload exhibits selective transport when comparisons are drawn with available channel material. It also reports the results of movement of magnetic tracers introduced in the same river channel and compares results with size and shape characteristics of trapped bedload.

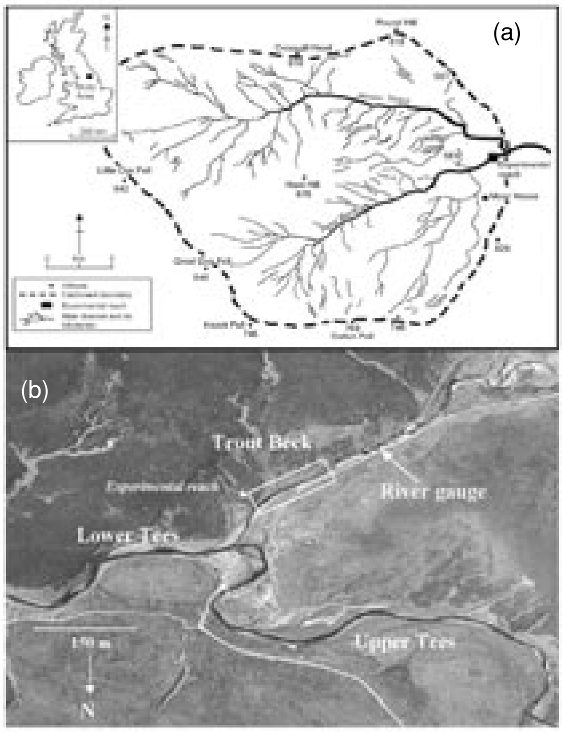


Figure 1. Map of the Trout Beck and River Tees catchments (a) and a view from the experimental reach (b) (reproduced by permission of NERC).

Şekil 1. Trout Beck ve Tees nehirlerinin havzaları (a) ve çalışma sahasından bir görünüm (b) (NERC'in izniyle yeniden üretilmiştir).

STUDY CATCHMENT

The main field experiments was carried out in Trout Beck (NY 759 336), a coarse gravel-bed stream, in the Moor House National Nature Reserve in the Northern Pennines of England. The Trout Beck is a headwater tributary of the River Tees. It drains from the south-west to north-east from the Cross Fell area of the North Pennines (Figure 1a and b). The catchment covers an area of 11.6 km^2 and rises to 848 m altitude.

The Trout Beck catchment is characterized by an upland area dissected by a main valley, which contains a coarse-bed wandering stream. The catchment is about 6 km long and the altitude ranges from 848 m at Great Dun Fell (head of the catchment) to 630 m at the confluence of the River Tees (see Figure 1a). Drainage density is high by British standards (3.57 km/km^2) and it increases markedly towards the headwater zone, probably due to a combination of high relief, higher rainfall and the impermeability of the rock in the area of superficial till deposits. The longitudinal profile of the Trout Beck is concave and mean channel slope at the experimental reach is 0.0095 m. The solid geology of the Northern Pennines is dominated by rocks of Carboniferous, consisting mainly of alternating shales, limestones, sandstone and coal. In the study reach 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 overall pattern is of a wandering, coarse-bed stream.

METHODOLOGY

Bed material sampling: In the experimental reach, bed material was sampled at low water stage according to the procedure outlined by Wolman (1954). Five sampling sections, 30 m apart, were selected. Generally, the upstream part of bars was chosen as a sampling section because it contains the coarsest gravel and exhibits little sorting. In each section, a 1m^2 quadrat was placed on the selected section channel bed and subsurface material was sampled in bulk to a depth of a few times the largest gravel diameter from which all surface material was removed (Figure 2). Sampled material then sieved and weighed. Material was classified using the Wentworth (1922) size classification. Material < 32 mm was sieved into five size classes, while the coarse clasts (>32 mm) were classified on the basis of their b (intermediate) axes into seven sizes using a shape box (Shakesby, 1989) and template caliper. In order to standardise the classification of clast shape the Zingg classification of clast form was used. Using the data on a (long), b (intermediate) and c (short) axes of coarse clast, b/a and c/b ratios were calculated and used to classify clasts as spheres, discs, rods and blades (Zingg, 1935). Cailleux's roundness and flatness indexes (Cailleux, 1947) were used to determine the roundness and flatness values of the clasts. Krumbein's sphericity index was used to determine the sphericity of clasts in each size group (Krumbein, 1941b).

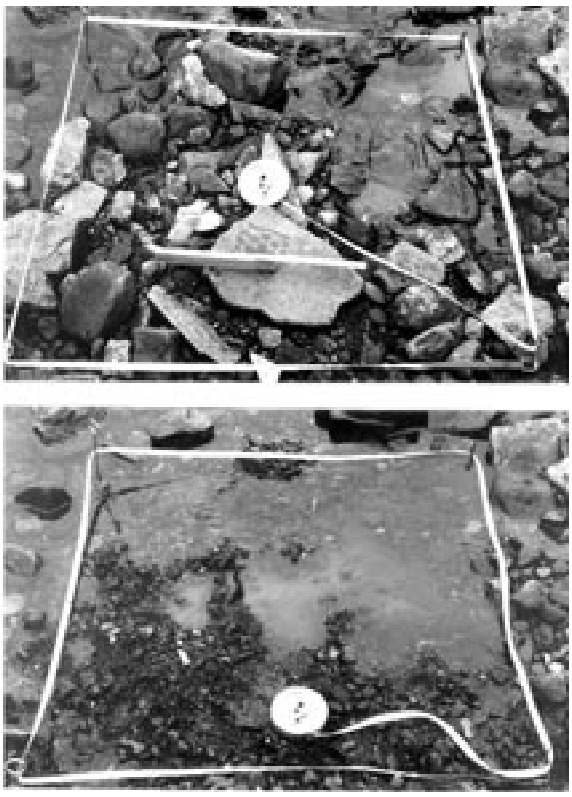


Figure 2. One of the cross-sections where surface (above) and sub-surface (below) bed material sampling was carried out at the Trout Beck (looking downstream).

Şekil 2. Trout Beck akarsuyunda yüzey ve yüzeyaltı yatak malzemesi örneklerinin alındığı yatak kesitlerinden biri (fotoğrafa bakış akım yönündedir).

Bedload sampling: Bedload was sampled twice, on two different occasions, 20 December 1997 and 30 August 1999, from behind a weir. The bed material is generally similar upstream and downstream of the Trout Beck weir which acts as a partial bedload trap (Warburton and Evans, 1998). Bulk samples of 97.6 kg (Trap 1) and 90.4 kg Trap 2) were collected from the centre of the stilling pond. Size and shape characteristics of the trapped bedload were determined using the methods explained above.

Magnetic tracer experiment: In order to investigate the effect of shape on the transport of coarse river gravel a field experiment was set up at the Moor House National Nature Reserve, North Pennines, England. The field experiment was carried out in an experimental reach on Trout Beck River. Discharge is gauged on the Trout Beck approximately 400 m upstream of the confluence with the River Tees (see Figure 1b). The site consists of a compound Crum weir. River flow and bedload movements were monitored from 24 November 1977 to 24 September 1999.

A total of 900 tracers were introduced in the experimental reach. The size range of the tracers was between 32 and approximately 256 mm, which represented the coarsest two thirds of the grain-size distribution. Selecting the coarsest end of the grain-size distribution is significant because this is where size and shape sorting are usually most pronounced. Three size classes were defined: 32 to les than 64 mm, 64 to less than 128 mm and greater than 128 mm. In the smaller size classes 400 tracers were prepared. Within each size class equal proportions of different shaped clasts were included. Careful screening of the clasts on the basis of the Zingg (1935) shape classification produced four distinct shape classes: spheres, blades rod and discs. Clasts plotting close to the shape boundaries were not used in the experiment. The tracers are similar in terms of lithology and density and match the coarse size friction of the natural bed material.

Each of the tracer clast was first drilled and a small RDAL 00029 ferromagnetic magnet placed inside. The magnet was sealed in place using silicon gel then the whole clast was painted with masonry paint and labelled with an identification number. All tracers were measured (a, b, c axes) and weighed in order to provide an independent means of identification if the paint labels were erased. The tracers were placed on the channel bed in a 3 m wide strip band 2 to 3 m in from the banks. Distances and new locations of the tracers at the three sites were documented on five occasions between 18th December and 6st July 1999. The Site was visited weekly to gauge movement and, where noticeable movement had occurred, the site was resurveyed as soon as discharge conditions permitted. The positions were mapped with reference to a series of monumented pegs set-out along the banks adjacent to the experimental reaches. The position of individual tracer clasts was surveyed using two methods; namely tape survey and EDM survey. Movements < 2 m from the start line were not included in the analysis. The aim of the experiment was not to reproduce the exact field conditions of the natural bed material, but to see how different clasts shapes behaved in a fluvial setting.

RESULTS

Size and shape characteristics of sampled bed material and trapped-transported bedload

In the experimental reaches bed material is coarse and poorly sorted in size and shape. Therefore, shape characteristics of the natural bed material are assumed to be somehow different than the magnetic tracers used for the field experiments. In terms of size, small size bedload is expected to be transported selectively compared to larger size coarse material. Spheres and rod-like clasts are also assumed to be transported more easily. In order to test these hypotheses the nature of trapped bedload was compared with surface bed material sampled in the Trout Beck reach.

Size: Figure 3 shows normal and cumulative percentage distributions of trapped bedload and bed material sampled (5 samples) from the Trout Beck reach. In the transported material most of the clasts are in the smaller size range. For example, 73.8 % of material is greater than 64 mm in the bed material, while it is only 56.3 % for Trap sample 1 and 57.3 % for Trap sample 2. However, D_{50} sizes are very similar. The mean values of a, b, c axes and weight of the bed material are greater than the trapped-bedload.

Statistical comparison of size and shape characteristics of bed material and trapped bedload are shown in Table 1. This clearly demonstrates that, within each shape class, there are statistical significant differences between weight and the a, b, and c axes of clasts between the trap-

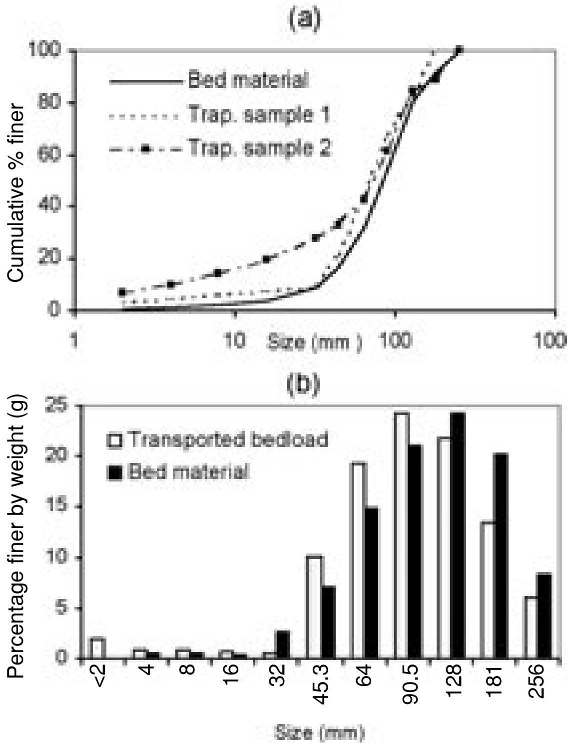


Figure 3. Cumulative percentage (a) and normal size distributions (*by weight*) of sampled-bed material and trapped-bedload (b) at Trout Beck (size indicated = upper limit of class; e.g. 4 indicates 2-4 mm size range).

Şekil 3. Trout Beck akarsuyunda örneklenen yatak yükü malzemesi ve taşınan malzeme boyutunun kümülatif yüzde ve normal dağılımı. (boyut: boyut kategorisinin üst sınırını göstermektedir. Örneğin, 4 rakamı 2-4 boyut aralığının üst sınırını göstermektedir).

Table 1. Statistical comparison of mean size and shape characteristics of bed material with bedload trapped at the experimental reach. (The critical values of 'T' at the 0.05 significant level is 1.97.The values shown in bold indicate a statistical significant difference between the compared parameters).

Çizelge 1. Çalışma sahasında taşınan ve yatakta mevcut yatak yükü malzemesinin ortalama tane boyutu ve tane şekli özelliklerinin istatistiksel karşılaştırılması. ('T' kritik değeri 0.05 önem düzeyinde 1.97 dir. Koyu renkle gösterilen değerler karşılaştırılan parameterler arasındaki farkın istatistiksel olarak önemli olduğunu belirtmektedir).

Parameters	Sphere	Blade	Rod	Disc
a-axis	**-4.00**	**-6.00**	-1.65	**-6.01**
b-axis	**-3.59**	**-6.27**	-1.81	**-5.89**
c-axis	**-3.16**	**-4.39**	-2.30	**-4.31**
Radius	-0.81	-0.94	0.01	-0.77
b/a ratio	**2.80**	-0.65	0.29	1.70
c/b ratio	1.75	0.90	-0.30	1.56
Roundness	1.53	1.48	0.28	**3.88**
Sphericity	**3.37**	0.39	0.13	**2.38**
Flatness	**-2.67**	-1.10	0.77	-1.62
Weight	**-3.12**	**-4.61**	**-2.98**	**-4.45**

ped bedload and sampled bed material. Indeed, in all shape class, clasts in the trapped-bedload are lighter in weight and also smaller in size (a, b, and c axes) than the sampled bed material (see Figure 3).

Shape: Table 2 compares the shape of transported clasts and reach material by size category and indicates although discs-shaped clasts dominate the shape distribution both in the bed material and trapped-bedload, the frequency of sphere-shaped clasts in the trapped material is noticeable greater than the bed material. Table 2 also suggests that regardless of size, blade and rod-shaped clasts are under-represented in the trapped material. A similar, but less marked, tendency is also evident for discs.

In terms of size, disc-shaped clasts are most important in each size group and become increasingly dominant with greater size. Rods, spheres and blades are more frequent than discs in the small and medium size categories. Comparison of bed material and trapped material also indicates that spheres are over-represented in the small and medium size group. Disc-shaped clasts, on the other hand, tend to be over-represented in the larger, and to some extend, in the medium size groups, while they are under-represented in the smaller size ranges (see Table 2).

Table 3 summarises mean roundness, sphericity and flatness of transported and sampled bed material in 16-64, 64-128 and >128 mm size groups at Trout Beck. Mean roundness values of trapped-material in each size group tend to be higher than the bed material. There tends

Table 2. Size-frequency distributions of trapped bedload and bed material in three size groups and four shape classes at Trout Beck. (Note: Values in brackets show percentage of distribution).

Çizelge 2. Trout Beck akarsuyunda taşınan ve yatak yükü malzemesinin tane boyutu sıklık değişiminin üç tane boyutu kategorisi ve 4 şekil gurubu içindeki dağılımı (Parantez içerisinde gösterilen değerler dağılımın yüzde olarak ifadesidir).

	Trapped- material (two traps combined)					Bed material			
Size (mm)	16-64	64-128	>128	Total	Size (mm)	16-64	64-128	>128	Total
Sphere	166 (31.6)	41 (33.1)	1 (9.1)	208 (31.5)	Sphere	95 (23.2)	50 (22.3)	11 (19.6)	156 (22.6)
Blade	59 (11.2)	7 (5.6)	0 (0.0)	66 (10)	Blade	54 (13.2)	42 (18.8)	7 (12.5)	103 (14.9)
Rod	75 (14.3)	11 (8.9)	0 (0.0)	86 (13)	Rod	82 (20.0)	25 (11.2)	2 (3.6)	109 (15.7)
Disc	225 (42.9)	65 (52.4)	10 (90.9)	300 (45.4)	Disc	179 (43.7)	107 (47.8)	36 (64.3)	322 (46.6)
Total	525	124	11	660	Total	410	224	56	690

Table 3. Mean roundness, sphericity, and flatness in different size classes of trapped material and bed material at Trout Beck.

Çizelge 3. Trout Beck akarsuyunda taşınan yatak malzemesi ve yatak yükü malzemesinin ortalama yuvarlaklık, küresellik ve basıklık özelliklerinin değişik tane boyutu kategorilerine göre dağılımı.

	Trapped material			Bed material		
Size (mm)	16-64 mm	64-128 mm	>128 mm	16-64 mm	64-128 mm	>128 mm
Roundness	235	211	170	207	171	147
Sphericity	0.70	0.72	0.68	0.67	0.67	0.68
Flatness	212	208	321	224	247	261

to be a decrease in roundness with size both in the transported material and bed material. Mean sphericity values for all size categories are low for both transported and bed materials as compared to magnetic tracers. However, mean sphericities of transported clasts within in each size group tend to be greater than those of the bed material (see Table 3). Except for the large size group, mean flatness of trapped clasts in the small and medium size groups is slightly lower than the bed material. There is no consistent variation of flatness with size in the transported material, while in the bed material clast flatness increases slightly with size.

There is no statistical significant difference in the roundness of sphere, blade and rod-like clasts between the trapped bedload and the sampled bed material (see Table 1). Disc-like clasts in the trapped bedload are more round and spherical than bed material. Sphere-like clasts in the trapped bedload are more spherical compared to the bed material, while there is no statistical significant differences between sphericity of blade and rod-like-clasts of the trapped bedload and the sampled bedload. Overall, comparison of trapped bedload and sampled bed material suggests that clasts in the trapped bedload are more spherical and rounded (sphere and disc-like clasts), lower in weight and smaller in size (for each shape class) (see Tables 2 and 3).

The magnetic tracing experiments

River flow and magnetic tracer transport distances: River flow was only competent to transport magnetic tracers during winter storm peaks. The river flow in the catchment is very flashy and numerous storm peaks were recorded during the monitoring period (Figure 4). The flashy nature of the river reflects the relative impermeability of the rocks, and superficial till deposits and soils, which, together with high relief, lead to high and quick responses of streamflow to heavy rainfall. The greater size of peak flows at Trout Beck is due to its larger catchment area and also channel shape. The fact that tracers were transported for only very short periods at the river is a typical characteristics of gravel bed rivers and it is also in accordance with previous bedload studies in similar environments (e.g. Newson, 1981; Schmidt and Gintz, 1995). It was found that peak flow discharge and also its duration has an important influence on both the number of tracers moved and also their transport distances. For each of the survey period, both the numbers of tracers and also their transport distances increased with peak flow discharge rather than mean flow at the experimental reach.

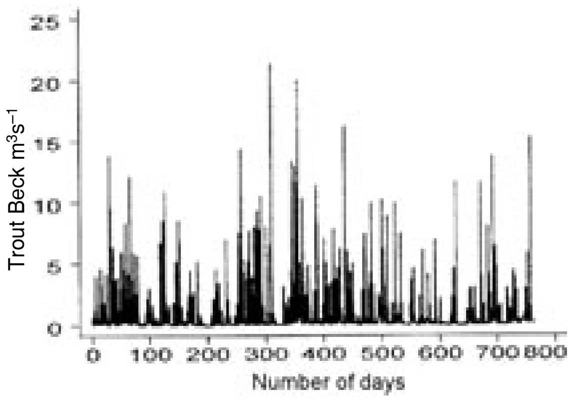


Figure 4. Discharge during the monitoring period November 1997-September 1999 at the experimental reach.

Şekil 4. Çalışma sahasında Aralık 1997-Eylül 1999 tarihler arasında ölçülen akarsu debisi.

Size-shape and distance of travel of magnetic tracers at the experimental reach: In the whole 429 (48%) out of the 900 tracers were recorded to have moved during the entire monitoring period. Altogether, 206 particles could not be found and 110 particles were buried. Most of the particles disappeared (73.7%) and buried (63.6%) were in small size group. Mean depth of burial was 7.3 cm.

The mean distance moved for the particles was 36.8m. The greatest observed movement was 399 m by a small rod. The number of particles moved in the medium size group is greater than that of small and large size group (small size: 167, medium size: 204 and large size: 58). However, particles in the small sized tracers moved further downstream. The mean transport distances for the small and medium size groups were 47.8m and 32.6m respectively, while it is only 19.6m for the large size group.

For the entire monitoring period, the cumulative mean transport distance and the survey period mean transport distances are shown in Figure 5. In general, there is a gradual increase in the total mean transport distance from one survey to another with an exception between surveys 3 and 4 where there is little variation. In terms of shape, in general, all shapes showed a decrease in distance and frequency of transport as size increases. It was found that, regardless of size, sphere, rod and to some extend disc-shaped tracers have been transported by far the greater distances and also more in number, while blades moved least. Results have clearly shown that within each size group spheres and to some extent rods travelled much longer distances than similar-sized disc and blades (Figure 6). The reason why the spheres and to some extend rods have longer mean transport distances but discs and blades do not, may be that, because spheres and rods are largely rolled rather than lifted, the rate at which spheres are moved by rolling is more directly related to the flow.

Regression analysis - factors affecting travel distance of tracers: The results of regression and multiple regression analyses are presented in Tables 4 and 5. Data were analysed for the experimental site and correlations between tracers shape, size parameters and transport distances were calculated. The data were Log10 transformed before each coefficient was calculated. Correlation values for each of the individual parameters show that both clast a-axis and Krumbein sphericity are the most useful predictors of transport distance. The *c*-axis measurements showed no significant correlation with

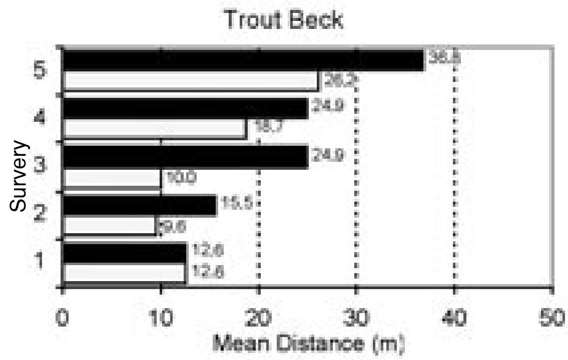
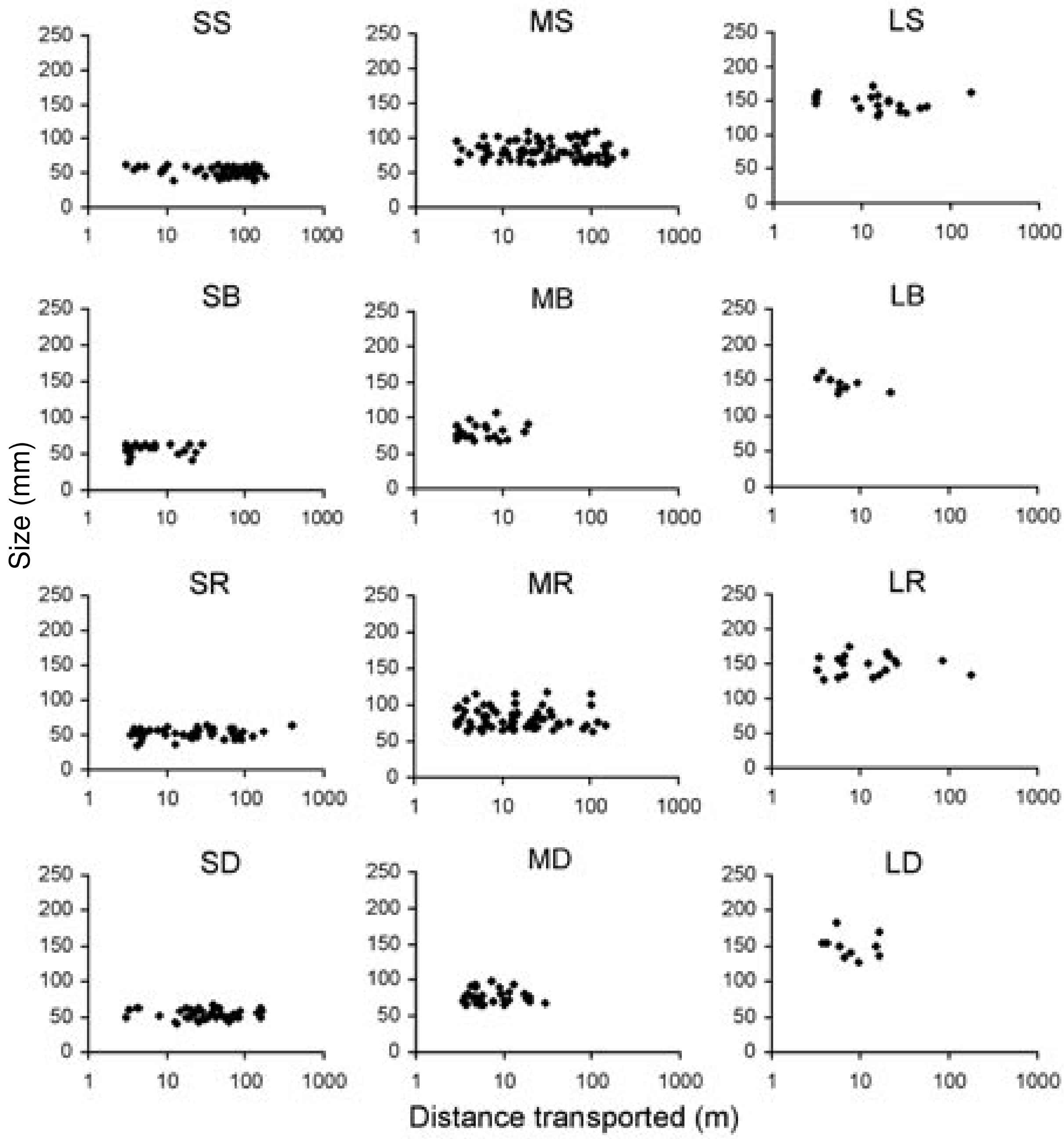


Figure 5. Cumulative and survey period mean transport distances of tracers during the fieldwork period at the Trout Beck site.
Şekil 5. Trout Beck alanında, arazi çalışması sırasında mıknatıslı çakılların kümulatif ve her ölçüm dönemi için ortalama taşınma mesafeleri.

Tables 4. Correlation of distance travelled by magnetic tracers (Log transformed) with size and shape (log transformed) variables for the experimental site. Bold values indicate significance of 0.05 level.
Çizelge 4. Çalışma sahasında mıknatıslı çakılların taşınma mesafelerinin tane boyutu ve şekilsel özelliklerine göre değişiminin deneştirilmesi.

Survey	A axis	B axis	C axis	b/a ratio	c/b ratio	Cailleux roundness	Krumbein sphericity	Cailleux flatness	Weight	Significant value
1	-0.147	-0.015	0.089	0.179	0.156	0.112	**0.257**	**-0.253**	0.055	*0.219*
2	-0.160	-0.023	0.140	**0.203**	**0.222**	0.186	**0.326**	**-0.336**	-0.044	*0.19*
3	**-0.207**	-0.087	0.110	**0.187**	**0.236**	0.149	**0.319**	**-0.336**	-0.097	*0.181*
4	**-0.360**	**-0.203**	**0.149**	**0.256**	**0.356**	**0.246**	**0.441**	**-0.464**	**-0.169**	*0.128*
5	**-0.413**	**-0.282**	0.066	**0.246**	**0.281**	**0.306**	**0.433**	**-0.379**	**-0.256**	*0.128*



SS: Small sphere MS: Medium sphere LS: Large sphere SB: Small blade MB: Medium blade
LB: Large blade SR: Small rod MR: Medium rod LR: Large rod SR: Small rod
MR: Medium rod LS: Large rod

Figure 6. Tracer sizes and transport distances for the final survey at the Trout Beck.
Şekil 6.Trout Beck akarsuyunda son ölçüm dönemi itibariyle mıknatıslı çakılların boyutları ve taşınma mesafeleri.

distance (see Table 4). There tends to be a negative correlation between transport distance and clast weight, flatness, a and b axes, while other parameters such as sphericity and roundness ratios show positive correlations with distance.

Table 4 also shows that, in general, correlation between individual predictors and transport distance tends to become stronger over time. Correlations between the independent variables and transport distance are consistently more significant at the experimental reach. This sug-

Table 5. Multiple regression analysis: factors affecting transport distance (Log 10 distance) of magnetic tracers at Trout Beck.

Çizelge 5. Çoklu regresyon analizi: Trout Beck akarsuyunda mıknatıslı çakılların taşınma mesafesini (Log 10 mesafe) etkileyen faktörler.

Parameters (Model structure)	Multiple R	F ratio	F significance	Standard deviation	Number of samples
Model 1: Distance: a-axis, roundness, weight	44.6	35.1	2.48E-20	0.464	429
Model 2: Distance: b-axis, rounr roundness, weight	42.4	31.3	3.27E-18	0.469	429
Model 3: Distance: c-axis, roundness, weight	50.3	48.0	9.87E-27	0.447	429
Model 4: Distance: sphericity, roundness, weight	49.9	44.7	3.78E-25	0.451	429

gests that the influence of the predictors tend to become stronger with distance. There tends to be a negative correlation between transport distance and clast weight, flatness, a and b axes, while other parameters such as sphericity and roundness ratios show positive correlations with distance. These trends are expected given our knowledge of transport processes. This is because, these parameters influence clast rolling. The greater the sphericity, roundness, and c/b ratio the more clasts move in a rolling mode. Flatness, weight, a and b axes of clasts show significant but negative correlations with transport distance. A clast with a long axis, greater size/weight and platy-shape is expected to have greater resistance to movement. Therefore they tend to be more stable compared to clast which are light, more equant and round, or flat but light.

Several multiple regression models were developed. Model parameters were selected so that they were independent and problems of inter-correlation were avoided. Results (Multiple R) at Trout Beck show a greater percentage of the variation in transport distance is explained by the regression models (see Table 5). The combination of the three independent variables that represent the greatest explanation of the variance at Trout Beck are c-axis, roundness and weight with a 50.3%.

Overall, the results of the multiple regression analysis clearly indicate that, together with roundness and weight, clast c-axis, and sphericity have the greatest correlation with transport distance. A-axis is also in some cases well correlated with distance but b-axis showed poor correlation with distance (see Table 5). In general, the level of explanation involving these models is generally low. Several others significant factors such as local flow conditions and bed roughness are not included in the models.

Spatial distribution of magnetic tracers in the river channel at the experimental reach

Figure 7 shows the spatial distribution of magnetic tracers for different survey periods at the experimental reach. This survey has been selected to show the general patterns of the tracers. Results are plotted in terms of shape class of the tracer clasts and size. Only clasts, which have moved greater than 3 meters beyond the start line, are considered. This corresponds to approximately 48% of the Trout Beck tracers. Originally 900 tracers were introduced at the site. The large numbers of tracers involved allow detailed appreciation of the movement patterns. Previous studies (e.g. Laronne and Duncan, 1992; Hassan et al., 1999) often do not include enough tracers for such patterns to be clearly described. Between the start line and section 3 the majority of the tracers are distributed fairly evenly across the channels. Beyond Section 3 the tracers become concentrated along the line of the main thalweg which is close to the right bank. The dispersion of the tracers at the Trout Beck is clearly concentrated in the deeper sections. Tracer distributions beyond section 9 tend to be more dispersed due to shallower depths as the channel widths increase (see Figure 7).

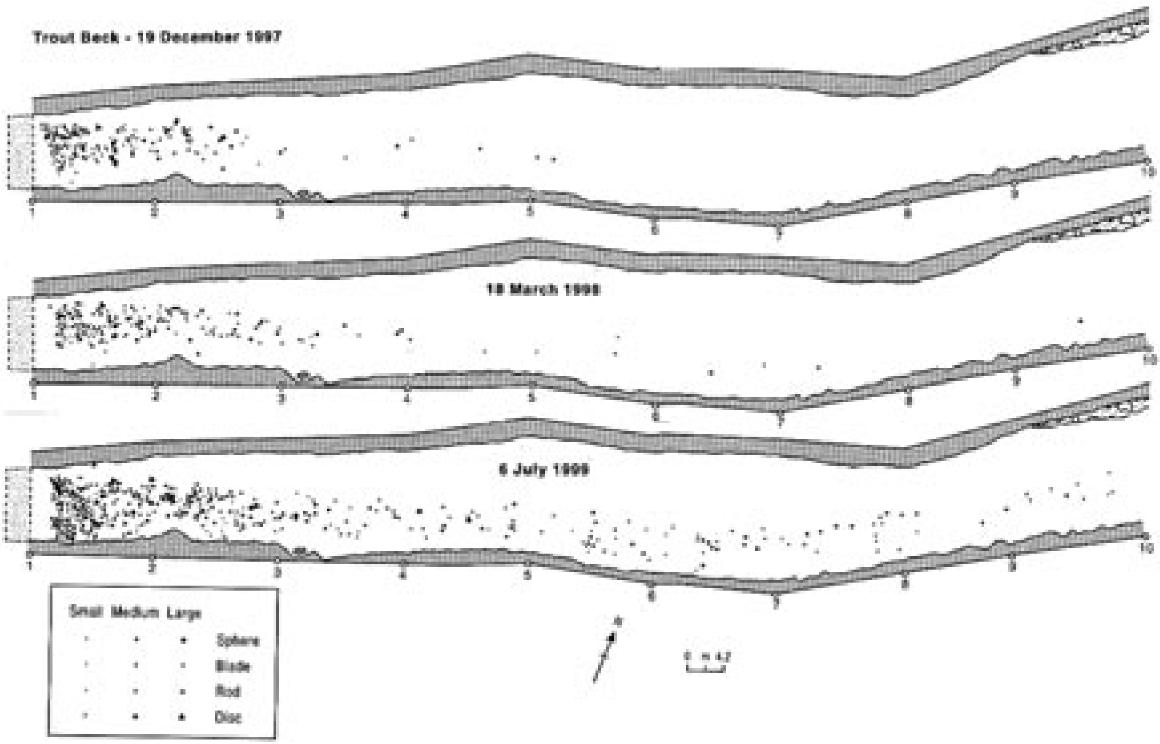


Figure 7. Spatial distribution of magnetic tracers at the experimental reach. (The shadow box is the “seeded” zone where tracers were introduced. Symbols show the size and shape of individual clasts).

Şekil 7. Çalışma sahasında mıknatıslı çakılların yatak boyunca dağılımı (Gölgeli alan, mıknatıslı çakılların akarsu yatağına bırakıldığı beslenme zonunu göstermektedir. Semboller çakılların şekil ve boyutlarını göstermektedir).

Spatial distributions at the experimental site shows that tracers are distributed more extensively. However, tracer densities tend to decrease with distance transported. In general, the uneven distributions of the tracers across the channel suggest that bedload transport at the experimental site is rather intermittent and the whole bed is quite stable. In other words, tracers are moving over a fairly ‘static’ bed.

In terms of size, it is clear that there is preferential movement of the small and medium size classes. Although some large clasts moved, the majority of the transport is confined to the first 30 metres downstream (see Figures 6 and 7). The general pattern shows a decrease in the frequency of movement with distance down the channel.

In terms of shape, spheres-and rods-shaped clasts are transported by far the greatest distance. Discs show a lesser degree of transport compared to spheres and rods and blade-shaped clasts appear to have moved the shortest distances and in the least numbers. Indeed, there is a significant decrease in the number of disc and blade-shaped tracers with distance downstream (see Figure 7).

Comparison of trapped transported material, resident material and magnetic tracers

In the trapped material the majority of clasts (almost 80%) fell in less than 64mm size category, while in the bed material the distribution is more even. In terms of shape, the number of transported magnetic tracers are greater in number and moved the longest mean transport distances in the sphere and rod clasts. In the trapped-material, spheres are also over-represented compared to the sampled bed material.

In general, natural bed material in Trout Beck is for less uniform in shape than the magnetic tracers. Figure 8 shows Zingg diagrams of the shape of all trapped material, sampled bed material

Table 6. Sphericity, roundness and flatness characteristics of trapped bedload, sampled bed material and magnetic tracers at Trout Beck (R: roundness, S: sphericity, F: flatness).
Çizelge 6. Trout Beck akarsuyunda taşınan yatak malzemesi, yatak yükü malzemesi ve mıknatıslı çakılların yuvarlaklık, küresellik ve basıklık Karakteristikleri (R: yuvarlaklık, S: küresellik, F: basıklık).

	Sphere					Blade					Rod					Disc				
	b/a	c/b	R	S	F	b/a	c/b	R	S	F	b/a	c/b	R	S	F	b/a	c/b	R	S	F
Trap sample	0.81	0.80	295	0.81	143	0.58	0.50	160	0.64	301	0.54	0.82	167	0.67	180	0.84	0.49	251	0.69	257
Bed Material	0.78	0.78	223	0.78	151	0.59	0.49	135	0.55	319	0.56	0.82	170	0.63	174	0.83	0.48	200	0.68	268
Magnetic tracers	0.86	0.84	597	0.85	129	0.50	0.37	216	0.45	427	0.45	0.83	263	0.55	201	0.85	0.35	509	0.63	327

Table 7. Overall summary of the results from the field experiments.
Çizelge 7. Arazi calışmaları sonuçlarının genel sunumu.

Magnetic tracing experiments	Sphere	Blade	Rod	Disc
Mean transport Distances (m)	56.6	0.14	0.55	0.37
Maximum transport distances (m)	243	0.12	0.72	0.66
Transported bedload enrichment factor compared to sampled bedload	1.31	0.64	0.79	0.93

and magnetic tracers used for the experiment at Trout Beck. It can be seen that very few clasts in both the bed material and also the trapped material tracers are “true” spheres, blades, rods and discs (which would plot in the extreme corners of the Zingg diagrams). Many of the spheres and discs were blocky in nature due to their sandstone lithology. Although, magnetic tracers are naturally formed in shape, geometrically they are closer to perfect sphere, blade, rod and discs compared to natural bed material. This is because, clasts plotting close to the shape boundaries were not used for the experiments (in order to make four distinct shape classes on the basis of Zingg (1935) shape classification).

In terms of transported tracers, differences in the density of points between various shapes are very clear. The majority of transported tracers are in the compact and rod shapes. Conversely platy (disc) and blades are poorly represented. The numbers of rods in the transported tracers are greater but these are not well-represented in the natural bed material (see Figure 8).

Table 6 shows shape characteristics of bed material, trapped bedload and the magnetic tracers used in the experiment. Higher b/a and c/b axes ratios and also greater roundness and sphericity values indicate that, clasts in the sphere-shaped group of the magnetic tracers are more spherical and round than the bed material and trapped material. Blade shaped-clasts, in trapped and bed material have greater c/b axis ratio than magnetic tracers used for the experiments. This suggests that blades in both bed and trap-

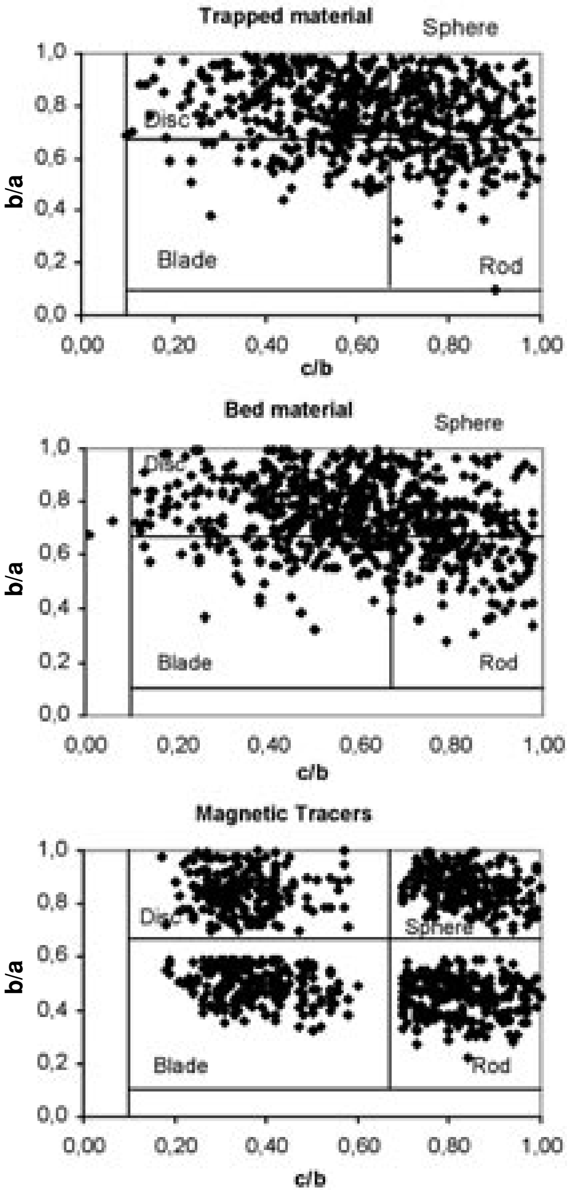


Figure 8. Shape distributions of the trapped-bedload, sampled bed material and magnetic tracers in the monitoring site of Trout Beck. (Distributions based on Zingg classification of clast form).

Şekil 8. Trout Beck ölçüm sahasında taşınan yatak malzemesi, örneklenen yatak yükü malzemesi ve mıknatıslı çakılların şekilsel özelliklerinin dağılımı (Dağılımlarda Zingg çakıl şekli sınıflaması esas alınmıştır).

ped material are more marginal to rod shape, compared to magnetic tracers. Likewise, many of the rods and blades in bed material and trapped material are “marginal” characterised by high b/a axes tending towards sphere and disc respectively (see Table 6). The higher c/b ratios in disc-shaped clasts in bed and trapped material also indicates that they are marginal to sphere shape, while discs in magnetic tracers tend to be flat.

DISCUSSION

Comparision of size and shape selectivity of trapped bedload with reach material

Assuming that the trapped-bedload is reasonably indicative of the size characteristics of bedload transport in Trout Beck River, size composition of trapped-bedload clasts at the monitoring reach appeared to be smaller than the bed material. In the trapped-bedload the majority of the clasts are in the smaller size ranges (see Table 2 and Figure 3). This may indicate a degree of size selectivity, as found by other coarse bedload studies (Li and Komar, 1986; Ashworth and Ferguson, 1989; Shih and Komar, 1990 and Ferguson et al, 1998). Another possible reason might be that smaller clasts might be transported on average greater distances than larger clasts leading to their greater representation in the trapped bedload.

To some extent shape composition of the trapped bedload and how it varies between the different size fractions simply reflects lithological control. The dominant sandstone lithology in the Trout Beck catchment tends to produce large tabular, flat slabs, which result in the dominance of flat clasts in the cobble fraction of the reach material. Disc-like clasts are more common in both sampled bed material and also in the trapped bedload, while blade-and rod-like clasts represent the lower percentages respectively (see Table 2). Although sphere-like clasts have the second in importance both in the trapped bedload and in the sampled bed material, the ratio is much smaller when compared to discs. As clast size increases the percentage of disc-like clasts increases markedly which is similar with the size distribution of sampled material in the experimental reach (see Table 2). The reason for the greater frequency of discs in the larger size clasts might be attributed to the effect of bedrock structure on clast shape. Comparison of trapped-bedload and bed material shows that, except in the small size group where disc-like clasts are under-represented, within all size groups of the trapped bedload, sphere- and disc-like clasts are more common, while blade-and rod-like clasts are under represented. A possible explanation for the over-representation of disc-and sphere-like clasts in the trapped-bedload might be the higher rolling capability of sphere-shaped clasts due to their greater sphericity. Comparison indicated that disc-like clasts in the trapped bedload are more spherical, more rounded in shape and also are lighter in weight and as well as smaller in size (a, b, and c axes) than those in the sampled bed material (see Table 3). In contrast to other shapes, there is a statistical significant difference in the degrees of roundness, sphericity size and weight of discs-like clasts between the trapped-bedload and sampled bed material (see Table 1). Thus, compared to the sampled bed material, greater sphericity and roundness of discs in the trapped material and also their smaller size/weight suggests that, these clasts might have been rolled due to their marginal shapes (sphere-like clast forms) (Sneed and Folk, 1958; Ashworth and Ferguson, 1989; Schmidt and Gintz, 1995). In terms of blade-and rod-like clasts, Table 1 shows that although blade-and rod-like clasts (as similar to disc-like clasts) are significantly smaller in size and also light in weight than those of in the sampled bed material, they are still under-represented in the trapped bedload. The reason might be attributed to their lower sphericity and roundness degree. In other words, despite their small size and less weight, blade-and rod-like clasts were not as mobile as disc-like clasts due to their angularity. This highlights the importance of sphericity and to some extent roundness on clast transport. Statistical comparisons also suggested that there is no statistical difference in the sphericity and roundness degrees of blade-and rod-like clasts between the trapped-bedload and sampled bed material.

Size and shape selectivity in magnetic tracers compared with trapped-transported bedload

Comparison of magnetic tracers and trapped-bedload suggested that, although sphere-and disc-like clasts in the natural bed material are transported preferentially, influence of size selectivity in the trapped material is stronger than shape selectivity when compared to the magnetic tracers. There are several reasons that might be attributed to this difference. First of all, the natural clasts in the experimental reach deviate from an ideal shape which will reduce the influence of shape on transport. This is because small differences in shape produce fairly large differences in hydrodynamic behaviour. Secondly, natural bed material in Trout Beck is less uniform in shape (see Figure 8). In both the bed material and trapped material, few clasts are “true” spheres, blades, rods or discs. Many of the sphere-and disc-like clasts were blocky. Although, magnetic tracers are naturally formed in shape, geometrically they are closer to a perfect sphere, blade, rod and disc compared to natural bed material.

It was found that in the Trout Beck bed material, clasts fall at the extremes of the natural bed material shape distribution. Natural bed material shapes are dominated by compact blades – bladed forms. Therefore some natural shapes are underestimated in the tracers used. Nevertheless there are some examples of all tracers shapes in the natural bed material. Comparison also suggests that within each shape class, most of the trapped-bedload and sampled bed material have relatively low roundness values than the magnetic tracers. The possible reasons for this might include; the short course of travel by the bedload material in the Trout Beck catchment as compared with other rivers and the discontinuous inputs of fresh angular material along the channel. Sphericity of sphere-like clasts in the Trout Beck is relatively low and less rounded compared to the magnetic tracers, suggesting that the upland position of the Trout Beck is not sufficient to result in spherical clasts through abrasion. Another possible reason for the low sphericity values of the bed material is the sandstone lithology, which leads to flat clasts that are also resistant to abrasion compared with many other lithologies (e.g. limestone, shale). Blade-like clasts in trapped bedload and bed material have greater c/b axis ratio, suggesting blades in both bed and trapped material are more marginal to rod-like shape. Likewise, many of the rods and blades in bed material and trapped material are “marginal” characterized by high b/a axes tending towards sphere and disc respectively (see Table 6). The disc-like clasts in bed and trapped material were also found to be more marginal to sphere shape due to their higher c/b ratios.

These differences are assumed to be important factors in bedload transport studies because, in gravel bed rivers, natural bed material shape deviates considerably from the ideal shapes and hence may not conform to models established for sphere, blade, rod and disc settling and transport. In other words, these variations in shape may lead to fairly large differences in hydrodynamic behaviour of clasts. The experiments carried out with magnetic tracers of ideal shapes do not directly represent actual clast motion in a natural channel. Nevertheless they are a usefull starting point for the systematic investigation of this general problem.

CONCLUSIONS

Analysis of trapped-bedload and sampled bed material gave some important insights into the transport of natural bedload at Trout Beck experimental reach. In general, compared to the results of magnetic tracers, much stronger size selectivity was apparent and, to some extent, shape selective transport. Small clasts in the trapped bedload were over-represented compared to bed material (see Table 2). Disc- and, to some extent, sphere-like clasts were found to be more common in both sampled bed material and also in the trapped bedload. Blade- and rod-like clasts were found in the smallest proportions (see Table 2). It was also found that as clast size increases the percentage of disc-like clasts also increase. The reason for the greater frequency of discs in the larger size clasts was attributed to the influence of bedrock structure (sandstone) on initial clast shape. Compared to the sampled bed material, sphere- and disc-like clasts were over-represented, while blade- and rod-like clasts were under-represented in the trapped-bedload (see Table 2). Statistical comparisons also showed that sphere and disc-like clasts in the trapped bedload are significantly more spherical, rounder and smaller in size when compared to sampled bed material (see Table 1). This suggested that, due to their greater sphericity and roundness, as well as their smaller size/weight, sphere- and disc-like clasts in the trapped-bedload were potentially more mobile. Indeed, discs found in the trapped bedload tended to be more spherical. Although blade- and rod-like clasts in the trapped bedload are smaller in size (thus lighter in weight) than those in the sampled bed material, they were still under-represented (see Table 2). This suggests, apart from size, other characteristics of clasts such as sphericity and roundness should also be taken into account. In other words, the lower transport capability of blade- and rod-like clasts in the trapped bedload is attributed to their lower sphericity and roundness. This highlights the importance of sphericity and to some extent roundness on clast transport. Comparisons also showed that blade- and rod-like clasts have relatively lower sphericity and roundness values than sphere and disc-like clasts both in the sampled bed material and also in the trapped bedload (see Table 6).

Magnetic tracing field experiments provided the opportunity further to test the influence of clast shape and size on transport distance on a coarse-bed river. As similar to trapped bedload, results of the magnetic tracing experiments also showed evidence of both size and shape selectivity. Preferential movement occurred in the finer (32-64 mm) clast size classes with tracers located along the channel thalweg moving the greatest distance (see Figure 7). The majority of the large clasts (>128 mm) moved only shorter distances. Generally, all shapes showed a decrease in distance and frequency of transport as size increased (see Figures 6 and 7). Differentiating between weight, size and shape revealed some consistent patterns in transport. It was also found that differences between the mean transport distances of tracers of various shapes tend to become smaller, as size decreases. This indicated that influence of shape on clast transport distance tends to be less important in the finer size (32-64 mm) clasts, while in the coarser size classes (64-128 mm and >128 mm) clast transport distances were more strongly shape-selective. These finding are similar to those of Schmidt and Gintz (1995).

In terms of shape, during virtually all survey periods, sphere-shaped clasts were transported the greatest distance and in greatest numbers. Rods and discs also moved preferentially but blades moved only short transport distances (see Figure 6). These patterns were consistent over the monitoring period. Similar experiments by Schmidt and Ergenzinger (1992), Carling et al (1992), Schmidt and Gintz (1995) and Stott and Sawyer (1998) also concur with present results, although clast shapes do not correspond exactly between experiments. Overall, comparison of transported bedload and sampled bed material using the enrichment factor, indicated that sphere-shaped clasts are over-represented both in the trapped bedload and also in the magnetic tracers moved, while discs, rods and blades are consequently under-represented in decreasing proportions (Table 7).

Although the present magnetic tracing experiments have yielded valuable information on shape and size selectivity, the shapes of the tracers were deliberately selected. However, in coarse-bed rivers, natural bed material shape deviate considerably from ideal shapes and does not comply exactly to sphere, blade, rod and disc-shaped clasts. In many natural settings variability in clast form is less pronounced and patterns of downstream changes in clast shapes are not apparent (Huddart, 1994).

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