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Downstream changes in bed material size and shape characteristics in a small upland stream: Cwm Treweryn, in South Wales

Dağlık bir bölgede, kısa bir akarsu mecrası boyunca yatak malzemesi yükünün şekil ve boyut özelliklerinin değişimi: Cwm Treweryn Nehri, Güney Galler

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ABSTRACT

The aim of this study is to investigate the downstream changes in bedload clast size and shape along the Cwm Treweryn stream, Brecon Beacons, South Wales. A total of 21 sites (including six tributary entry points) were used to evaluate downstream changes in bedload size and shape (form, roundness and sphericity) characteristics. At each sites, 100 surface clasts with b axes (intermediate) greater than 32 mm were sampled. Many of the earlier studies found that, due to abrasion and sorting processes, particle size decreases and roundness increases in a downstream direction. However, in contrast to these studies, the Cwm Treweryn stream does not conform this simple downstream pattern, instead shows irregular and complex changes in both size and shape along the channel. In terms of size characteristics, bed material at all 21 sites represented a wide range of size fractions and hence poor sorting. The dominance of disc-shaped clasts with blades the second most frequent shape along the entire channel length is attributed to the structural and lithological characteristics of the predominance of Old Red Sandstone. As a result, comparatively small downstream changes were determined in bedload clast size and shape (roundness, sphericity) and these changes are attributed to the combined effect of different factors, including the lithology of the bedload (Old Red Sandstone), the short river course, and occasional inputs of angular fresh material from the channel banks and bed.

Key words: Bedload, gravel-bed streams, particle shape, particle size, roundness, sphericity, Wales.

ÖZ
Bu çalışmanın amacı, Galler'in Brecon Beacons yöresinde küçük bir akarsu olan Cwm Treweryn'in yatağı boyunca yatak yükü (çakıl boyutundaki iri unsurlar (>32 mm)) malzemesinin şekil ve boyut özelliklerinin incelenmesidir. Bu amaçla, tali kollar dahil, yatak boyunca toplam 21 lokasyonda yatak yükünü oluşturan malzeme incelenmiştir. Her lokasyonda çapı (b-ekseni) 32 mm'den büyük olan toplam 100 çakıl örneği alınmıştır. Daha önce yapılan birçok araştırma, aşınma ve seçici taşınmadan dolayı, akarsu yatağı boyunca (kaynaktan ağıza doğru) yatak yükünü oluşturan unsurların boyutlarının genellikle küçülme eğiliminde olduğu ve malzemenin yuvarlaklığının arttığını göstermiştir. Bununla birlikte, Cwm Treweryn nehrinde yapılan ölçümler, anılan modeldeki basitliğin aksine, yatak yükünü oluşturan unsurlar şekil ve boyut özellikleri bakımından daha karmaşık ve düzensiz bir değişim örneği göstermiştir. Yatak malzemesinin boyut özellikleri 21 lokasyonda oldukca geniş bir dağılım ve dolayısıyla zayıf bir seçici taşınma örneği göstermektedir. Bütün yatak boyunca, disk şekilli çakılların birinci ve bıçak sırtı şeklindeki çakılların da ikinci büyük oranda olması ise, havzada hakim litoloji olan Old Red kumtaşının yapısal ve litolojik özelliklerine bağlanmıştır. Sonuç olarak, önceki çalışmalarla karşılaştırıldığında, Cwm Traweryn nehrinde yatak yükünü oluşturan unsurların boyut ve şekilsel özelliklerinin (yuvarlaklık ve küresellik) akarsu yatağı boyunca küçük bir değişim gösterdiği saptanmıştır. Bu durum değişik faktörlerin biraradaki etkisine bağlanabilir. Bunlardan bazıları; yatak yükünü oluşturan malzemenin litolojik özellikleri (Old Red kumtaşı), akarsu boyunun kısalığı ve akarsuya yatak ve teraslardan eklenen yeni malzemedir.

Anahtar kelimeler: *Yatak yükü, çakıl ağırlıklı akarsu, çakıl şekli, çakıl boyutu, küresellik, yuvarlaklık, Galler.*

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INTRODUCTION

Longitudinal distribution (downstream) in bedload size and shape characteristics has been a long-standing interest of fluvial geomorphologists and sedimentologists. These changes of bed material characteristics observed at any one time reflect the cumulative impact of many processes and events which have operated over an indefinite time period (Knighton, 1980). The factors and processes responsible, which have been considered by many authors (e.g. Wentworth, 1919; Krumbein, 1941; Sneed and Folk, 1958; Bradley et al., 1972; Mills, 1979; Knighton, 1980, 1982; Kodama, 1992) during the current century, can be classified into: a) lithological factors that affect the initial shape and size of bedload clasts, their ease and pattern of breakage and their resistance to abrasion; b) bedload source factors, including the range of sources and calibre of material supplied, the downstream pattern of inputs and their spatio-temporal variability; c) river channel processes, including sorting, abrasion and breakage, d) the influence of tributary inputs on the bed material characteristics of the main stream; e) flow variables; and f) inherited geomorphological characteristics of a catchment.

It is generally accepted that bed material size distribution tends to decline in a downstream direction where lateral inputs of coarse sediment from tributaries or valley sides are unimportant (Sternberg, 1875; Mackin, 1948; Knighton, 1980; Pizzuto, 1995). Earlier studies (e.g. Sternberg, 1875; Davis, 1899; Mackin, 1948) attributed this reduction to the competence which depends on velocity alone and velocity on slope alone, so that slope of a graded river must reflect the size of bedload supplied from upstream (Ferguson et al., 1998). However, following considerable detailed laboratory and field based investigations, it was found that beside velocity, this downstream reduction in particle size is also caused by a combination of abrasion and sediment transport processes. Abrasion reduces the size of particles, through chipping, splitting, crushing, grinding and breakage, etc. (Kuenen, 1956; Werritty, 1992; Shaw and Kellerhals, 1992; Kodama, 1992). Whilst selective sediment transport or sorting processes, preferentially transport finer particles a greater distance downstream than coarser particles. Of these two processes, sediment transport has been found to be the dominant process leading to this downstream fining (Russell, 1939; Bradley et al, 1972; Adams, 1978; Brierley and Hickin, 1985; Dawson, 1988; Ferguson et al., 1998). Despite this finding, debates on the relative importance of abrasion or sorting over downstream fining have continued. Gilbert (1877, 1914) stressed the possibility of particle sorting through size selection during entrainment and transport, though it was not until the 1970s/1980s that scientists acknowledged the importance of sorting as the prime cause of downstream fining (Ferguson et al., 1998). Indeed some field and laboratory simulation experiments have illustrated that rapid downstream fining cannot only be explained by abrasion, but selective sediment transport (sorting) should be considered (Bradley et al., 1972; Adams, 1978; Knighton, 1984; Dawson, 1988).

Although abrasion and sorting processes are considered to be the main factors which are responsible for downstream decrease of bed material size, other studies have shown that downstream changes are more complex due to factors such as lateral inputs of fresh angular bank material; a large number of tributary inputs; a short river course; and a variation in clast size reduction as a function of different lithology (Sneed and Folk, 1958, Bradley et al., 1972; Knighton, 1982; Rice and Church, 1998; McEwen and Matthews, 1998). Though considerable progress has been made in developing physically realistic models of downstream fining of particles (Parker, 1991; Hoey and Ferguson, 1994; Paola and Seal, 1995; Cui et al., 1996) as a result of the previous factors many of these models have based on single-source situations (Hoey and Ferguson, 1994) and relatively simple gradients of downstream fining due to the complexity of mechanics (Rice and Church, 1998).

Many of the earlier studies only considered downstream changes of bed material size and the importance of sorting as a result of particle shape has been underestimated. Studies which highlight the importance of particle shape on sediment transport include, Krumbein (1942), Helley (1969), Komar and Li (1986), Ergenzinger et al. (1989), Ergenzinger and Schmidt (1990), Carling et al. (1992), Schmidt and Gintz (1995). Of these studies the majority only concentrate on the variation of particle roundness (Mills, 1979) and therefore ignore particle sphericity, form and flatness. Thus, the role of particle shape is not completely understood.

All these facts clearly highlight the need for a further systematic study to determine the effect of bed material shape on bedload transport in gravel-bed rivers. The present study analysis the downstream changes in bed material size and shape (form, roundness, sphericity and flatness) along the Cwm Treweryn stream channel. It also identifies possible potential sources (e.g. lateral contribution of bank and valley material, and tributary inputs) which are assumed to have a persistent influence on bed material distribution along the Cwm Treweryn.

STUDY CATCHMENT

The Cwm Treweryn is a tributary of the Senni, which itself is a tributary of the Usk, to which the Senni joins at Sennybridge town. The catchment is located on the northern slopes of the Brecon Beacons mountain area in the South Wales of the United Kingdom (Figure 1). The catchment covers an area of 10.55 km^2 and is of rectangular shape (Figure 2).

The Cwm Treweryn catchment is characterised by an upland plateau in the headwater region, deeply incised main valleys, steep valley-side slopes towards headwater reach, a fast-flowing stream with a high gradient and coarse bed material. The catchment is about 7 km long. Altitude ranges from 630 m at Fan Bwlch Chwyth (head of the catchment) to 200 m at Tredustan Hall at the gauging station (see Figure 2). Drainage density is high by British standards in the catchment (3.11 km/km^2) and it increases markedly towards the headwater zone due to high relief, higher rainfall and the impermeability of the rocks (Devonian Old Red Sandstones) and post-glacial superficial till deposits. Especially towards the headwater reach, gullying of the till deposits has produced particularly high densities (4.33 km/km^2) (see Figure 2).

Figure 1. A view of the Cwm Treweryn catchment (looking north).
Şekil 1. Cwm Treweryn havzasından bir görünüm.

The longitudinal profile of the Cwm Treweryn is concave with an average gradient of 2^o. The river falls about 150 m in its first 1.5 km where the channel is narrow and has high slopes, whereas in the lower reaches channel gradient falls to 1^0. The channel pattern contains many bends. Though in some sections straight reaches occur, they seldom exceed a length of 100 m. In the lower reaches of the catchment the main stream receives two large tributaries from its eastern side. In the upper reaches near the headwater zone, many small tributaries join the main channel on both sides (see Figure 2).

The solid geology of the Cwm Treweryn Catchment is entirely characterized by Old Red Sandstone rock of Devonian age (Barclay et al., 1988). The lowest division of the Old Red Sandstone, which consists of red marls, does not crop out within the district. The lowest bed exposed belongs to the Senni beds. These are succeeded in ascending order by the Brownstones, the Plateau Beds and Grey Grits.

The Senni beds are only seen in the lower parts of the valleys along the northern margin of the district. These are characteristically green sandstones and are easily distinguishable from the markedly redder Brownstones above. The green sandstones are fine to coarse-grained and are characterised by both parallel lamination and cross-bedding with mica prominent along the bedding planes.

Rainfall is very high and increases with altitude across the region. Average annual precipitation varies from 1575 mm at Tredustan Hall at the downstream (northern) end of the catchment to about 1880 mm at Cray (290 m altitude) and 2180 mm an altitude of 318 m at Cray Reservoir No. 1 old site. The rainfall regime for the Cwm Treweryn catchment displays a fairly pronounced winter (October-March) maximum. Novem-

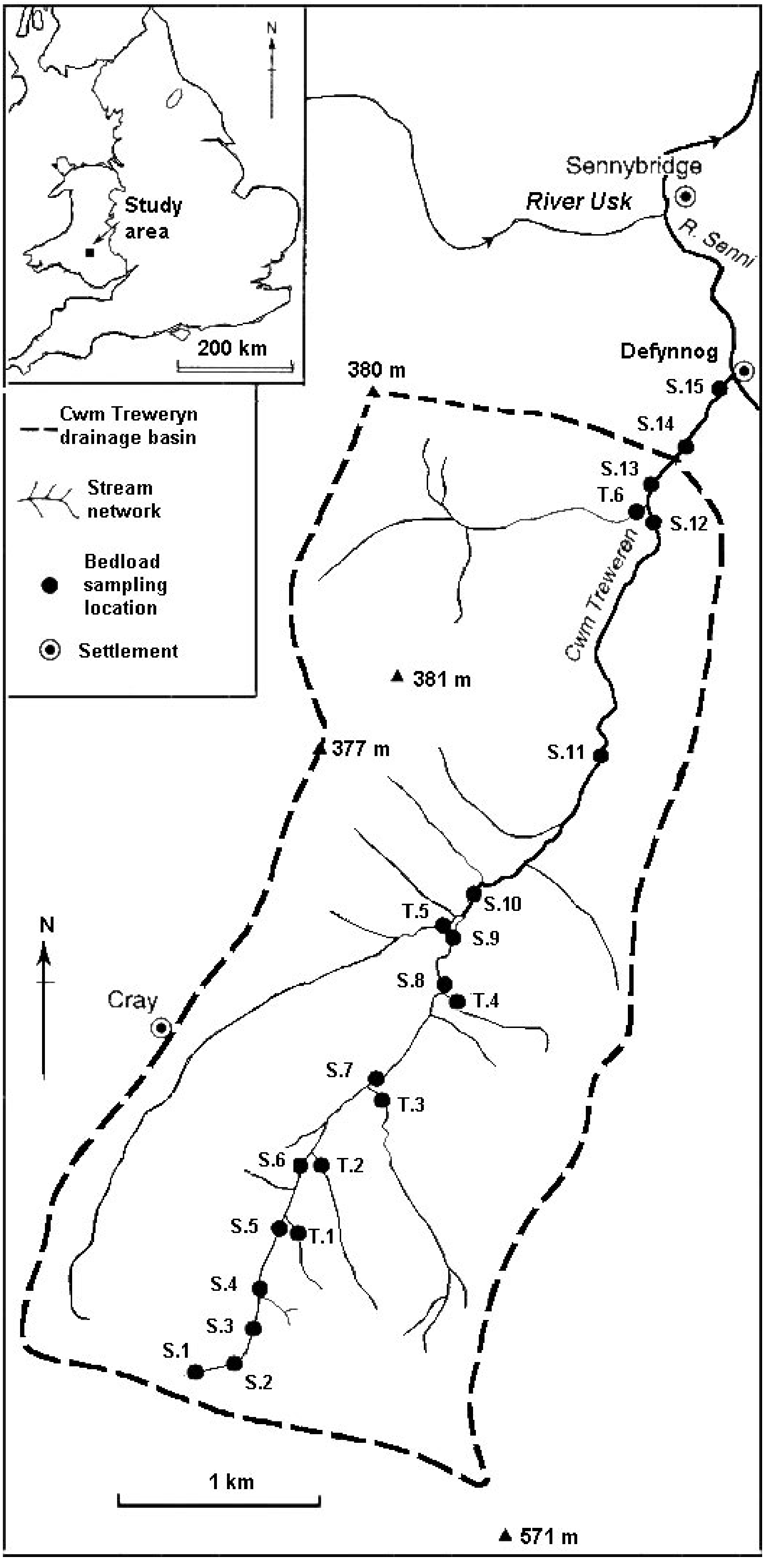

Figure 2. Cwm Treweryn Basin and Sampling Sites (S: Site, T: Tributary).
Şekil 2. Cwm Treweryn Havzası ve örnekleme yerleri (S: Örnek alma yeri, T: Akarsu tali kolu).

ber, December and January are on average the wettest months of the year and the four months from October to January contribute 49 % of the annual total. The summer six months (April to September) receive only 40.4 % of the year's rainfall, with about half of that falling in the months of August and September. Thus, the seasonal distribution of rainfall in the Cwm Treweryn catchment is typical of the British uplands (Walsh and Hudson, 1980). The steep slopes, impermeable geology and soils, high drainage densities, high rainfall and human effects combine to result in flashy runoff characteristics of the study catchment.

SEDIMENT SAMPLING PROCEDURE

21 sites (including six tributaries) were chosen along the main channel of the Cwm Treweryn stream (see Figure 2). The distance between successive sites varied for the following reasons: 1) in reaches where the channel gradient was constant and no important tributaries joined the channel, the sampling sites were more widely spaced; 2) in the headwater reaches Sites 1 to 8 were more closely spaced than further downstream because of a high channel gradient and numerous small tributaries entering the main channel (see Figure 2).

At each sites, 100 surface clasts with b axes (intermediate) greater than 32 mm were sampled according to the procedure outlined by Wolman (1954). This involved establishing a grid system at each site. The width of the grid was determined by the width of the channel at each site. The length of the grid was 18 m, because this provided good sampling, since this included a pool and a riffle at many sites, such as Sites 10, 11, 13, 14, and 15. At the upstream Sites 1-8, however, pool and riffle sequences were not observed because of the higher gradient of the channel. After establishing the grid system, at each site ten clasts were randomly selected at ten points across each of ten cross-sections spaced 2 m apart along the 18 m length of channel covered by the grid.

The size distribution characteristics were determined by measuring the three axes of each clast and classifying them into three size categories (32-64 mm, 64-128 mm and >128 mm). In analysing clast shape, the Zingg classification of particle form was adopted and at each site clasts were classified into four shape categories (sphere, blade, rod and disc) (Zingg, 1935). Clast roundness and flatness were determined using Cailleux's roundness and flatness indices (Cailleux, 1947) and sphericity was determined using Krumbein's sphericity index (Krumbein, 1941).

RESULTS

Downstream Changes In Size

Figure 3 shows the longitudinal changes of median diameter of bed material in the Cwm Treweryn stream and indicates, generally, an irregular downstream change in clast size distribution. Including tributaries, the rate of size decreases with downstream obtained by least square regression is noticeably low (R^2 = 0.037), while excluding tributaries the rate tends to be higher (R^2 = 0.074). In general, there is a sharp increase in mean size from site 1 to Site 6 which is then followed a sharp decrease (from Sites 6 to 9). There is no greater variation between Sites 9, 10 and 11, while a slight increase exist from Site 11 to 14 which is again followed by a slight decrease toward Site 15. The mean size at sites 1, 2 and 3 are relatively smaller than the following five sites (see Figure 3a). This is because these sites are in the headwater zone where channel has not incised to the bedrock and there are no lateral inputs of fresh material. On the other hand, mean size values increase noticeably between Site 4 and Site 8 where both valley slopes and channel banks contribute great amount of cobble size material into the channel (Figure 4). As compared to the upper reaches, there is no greater variation in mean size from Site 9 and onward, though there is a slight increase at Sites 12, 13 and 14. In general, at the upper reaches tributaries contribute relatively smaller size material as compared to the mean since they have not incised into bedrock and are small in size (see Figure 3b). However, towards downstream sites differences in size between bed material and tributaries decreases. Thus sediment is somewhat better sorted compared with farther upstream.

Downstream Changes In Shape

In order to define clast shape the Zingg classification of clast form was adopted. On the basis

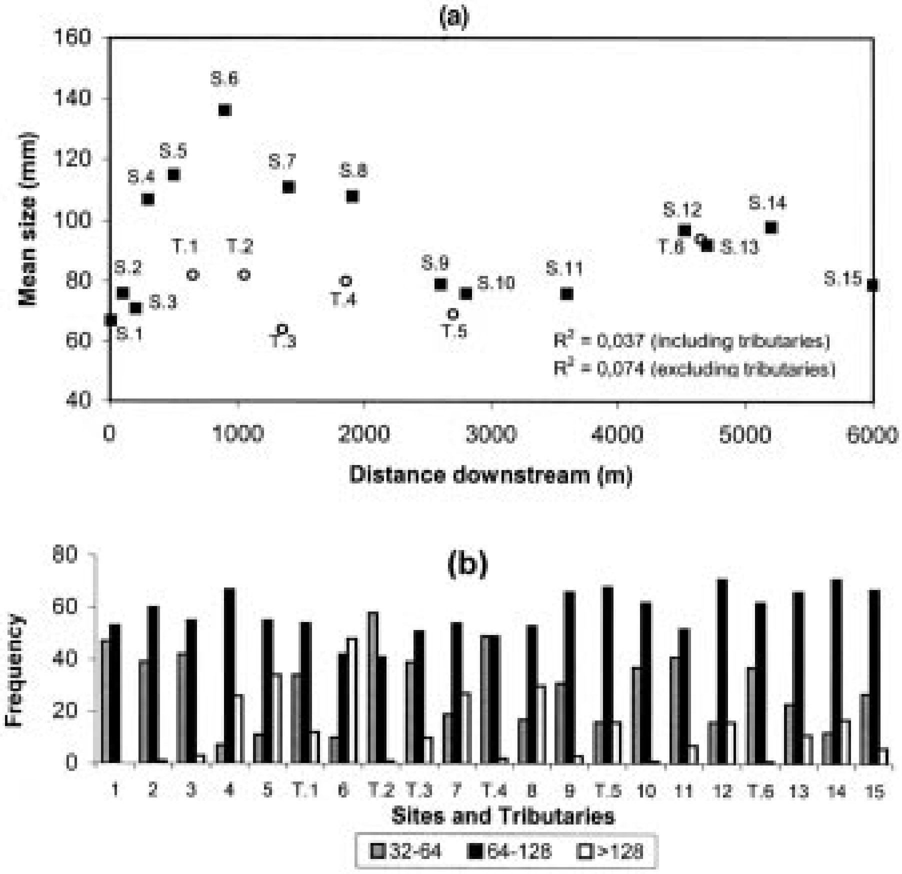

Figure 3. Downstream changes in median diameter of the coarse fraction (>32 mm) (a) and frequency of clasts by number (b) in the Cwm Treweryn stream.

Şekil 3. Cwm Treweryn akarsuyunda iri yatak malzemesi (>32 mm) medyan çapının akarsu mecrası boyunca değişimi (a) ve sayısal olarak sıklık dağılımları (b).

Figure 4. Channel banks in the catchment are a major source for the supply of angular material of a great range of sizes to the channel (Site 6, right bank).

Şekil 4. Havzadaki akarsu setleri, akarsu yatağına geniş oranlara varan değişik boyuttaki köşeli malzeme sağlayan başlıca kaynaktır (Lokasyon 6, sağ teras).

of this classification, for the three size categories (32-64, 64-128 and >128 mm), the a (long), b (intermediate) and c (short) axes were measured for each of the sampled clasts. Figure 5 shows the percentage frequency of the four shapes for the 100-clast sample in three size categories at each of the fifteen sites and at 6 tributaries.

Cobbles of >128 mm size are predominantly disc-shaped at all the sites where such large calibre material is present but percentage tends to decline with decreasing size. Combined with all sites, the percentage of disc-shaped clasts in small, medium and large size groups are 30 %, 53 % and 65 %, respectively. The percentage of cobble clasts that are discs exceeds 60 % at Sites 4-8, 11-14 and Tributary 6 and reaches 80 % at Site 5. At no site does the frequency of any other shape exceed 35 %. Blades are the se-

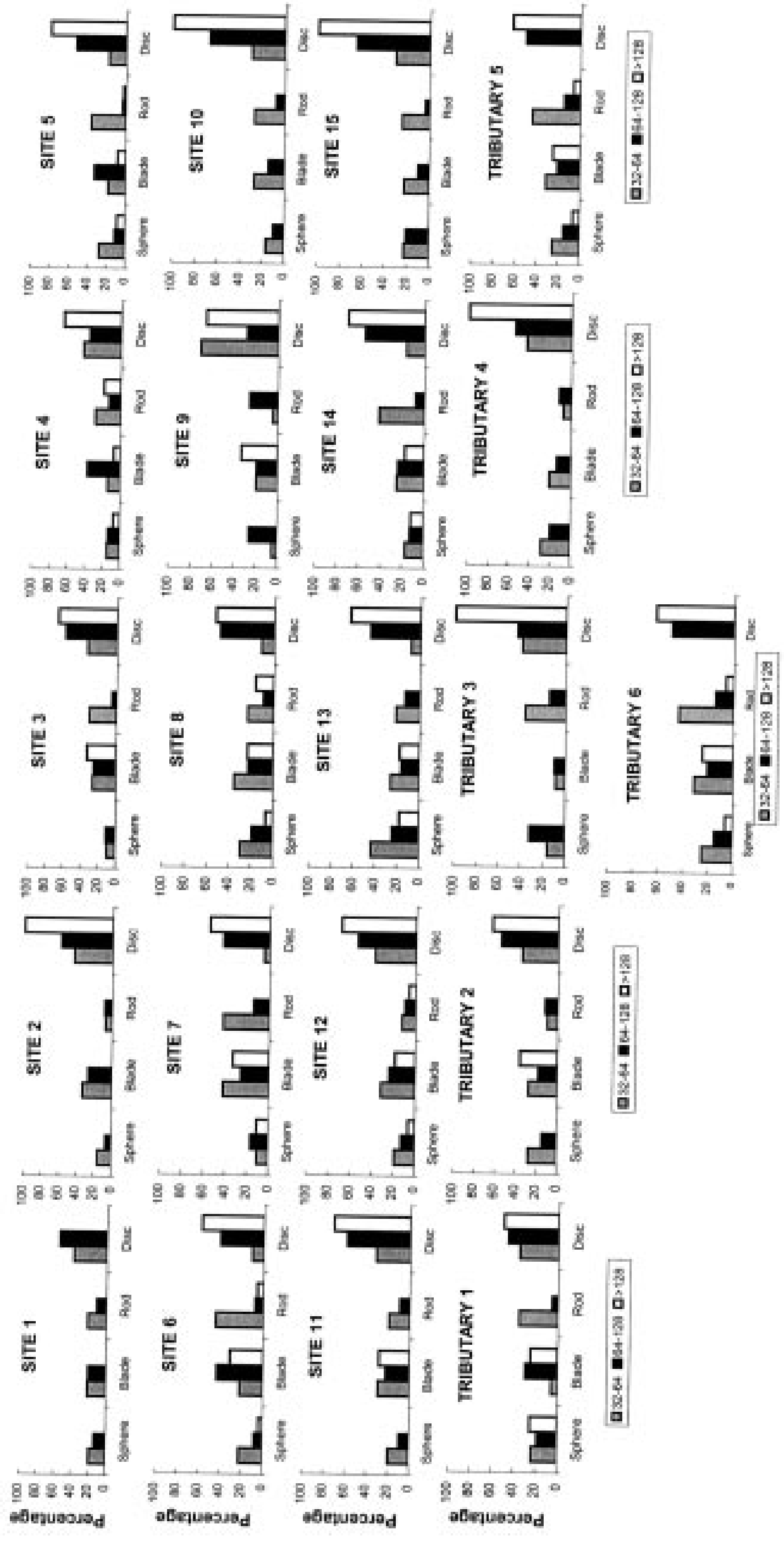

Figure 5. Downstream changes in clast shape for three size categories of the sampled bed material (mm).

Şekil 5. Akarsu mcrası boyunca örneklenen yatak malzemesinin şekilsel özelliklerinin üç değişik tane boyutu kategorisindeki değişimi (mm).

cond most frequent shape of cobbles, followed by spheres and rods.

Discs are of reduced frequency, but are still the most common shape, in the case of large pebbles (64-128 mm). Disc frequency in the large pebble class is 40-60 % at most sites, but exceeds 60 % at Tributary 5. As with cobbles, blades are the second most frequent shape, of equal frequency (35-40 %) to discs at Sites 3, 4 and 6, but more usually around 20 %. Spheres are of low frequency at the upstream sites but become more significant downstream, exceeding 20 % at Tributary 3, Sites 9, 13 and 15. Rods only exceed 15 % at Site 6 and are less than 10 % at several sites.

In contrast, in the case of smaller pebbles (32-64 mm), discs are of much lower frequency but become more significant upstream, exceeding 30 % at Sites 1-4, 9 and at Tributaries 1-4, while in downstream only two sites it exceeds 30 % (Sites 12 and 15) and frequencies fall below 15 % at 5 sites (Sites 6, 7, 8, 13 and Tributaries 5 and 4). The four shapes are of much more equal importance than for the larger calibre categories. Rods are most frequent at 6 sites (Sites 5, 6, 7, 10 and 14 and at Tributary 5) and spheres at a single site (Site 13). Blades are of highest frequency (36-40 %) at Sites 7 and 8.

Downstream Changes In Roundness

Mean roundness data for (a) all clasts and (b) the three size fractions 32-64, 64-128 and >128 mm at the 21 sites along the Cwm Treweryn are shown in Figure 6. Although, overall, there is a downstream increase in roundness, the incre-

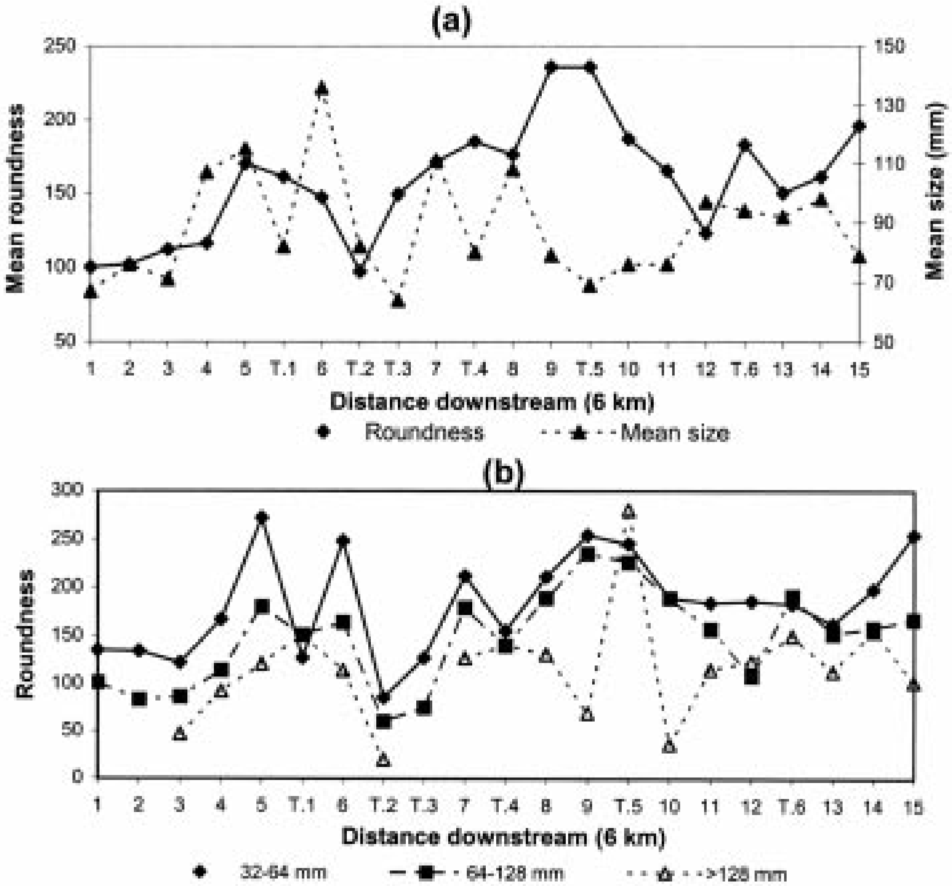

Figure 6. Downstream changes in (a) mean roundness and mean size (all clast sizes combined) and (b) mean roundness of three size categories.

Şekil 6. Akarsu mecrası boyunca yatak malzemesinin (a) ortalama tane yuvarlaklığı ve ortalama tane boyutunun değişimi (bütün tane boyutlarının ortalaması) ve (b) her tane boyutu kategorisindeki ortalama tane yuvarlaklığı değişimi.

ase is irregular and interrupted (see Figure 6a). Mean roundness increases from 112 to 230-240 between Sites 1-9, but declines to 125 by Site 12 before increasing to reach 197 at Site 15.

For individual clast size categories, however, there is no evidence of significant overall downstream increases in roundness, though the 64-128 mm category (except Tributaries 2 and 3) does increase between Sites 1 and 9 before falling sharply (Figure 6b). Clast roundness is consistently highest for the smallest (32-64 mm) size category and lowest for the larger (64-128 mm and >128 mm) size categories along the main channel (see Figure 6b). This negative correlation between clast size and roundness is confirmed when mean roundness of all clasts at each site is plotted against mean clast size (correlation coefficient: -0.32). Very large (>128 mm) clasts are least round except at the Tributary 5 site, where the clasts mostly discs, are exceptionally round, averaging 280 (see Figure 6b).

Downstream Changes In Sphericity

Downstream variation of mean sphericity for all clasts and the three size fractions 32-64, 64-128 and >128 mm at the 21 sites along the Cwm Treweryn are shown in Figure 7. Mean sphericity shows an irregular downstream increase. Correlation coefficient between mean sphericity for all size groups and distance downstream is 0.397 but the ratios tend to decrease in the large and the small clast size (0,279 for 32-64 mm and 0,270 for 64-128). Apart from a decrease in mean sphericity at Site 6 there is a steady increase in sphericity between Site 1 and up to the junction with Tributary 5. At Site 10 and particularly Site 11 mean sphericity falls sharply, averaging just 0.58 at Site 11. This appears to be linked to an increase in percentage of blade-shaped large cobble size material at Site 11 (see Figure 7). Below Site 11 sphericity increases again. Both Tributaries 5 and 6 show high sphericity values. The bed material is smaller at the tributary sites but there is no evidence that smaller material is more spherical (see Figure 7). Thus downstream change in sphericity in the 32-64 and 64-128 mm size categories shows a broadly similar pattern to that of mean sphericity, with no significant difference between mean sphericity of the two size categories.

DISCUSSION

Downstream changes in bed material characteristics, including clast size and shape, observed at any one time are the result of the cumulative effect of many processes and events that take place over a time period that may be difficult to define (Knighton, 1982, 1984). The most important factors influencing downstream changes of bed material characteristics are (a) the location

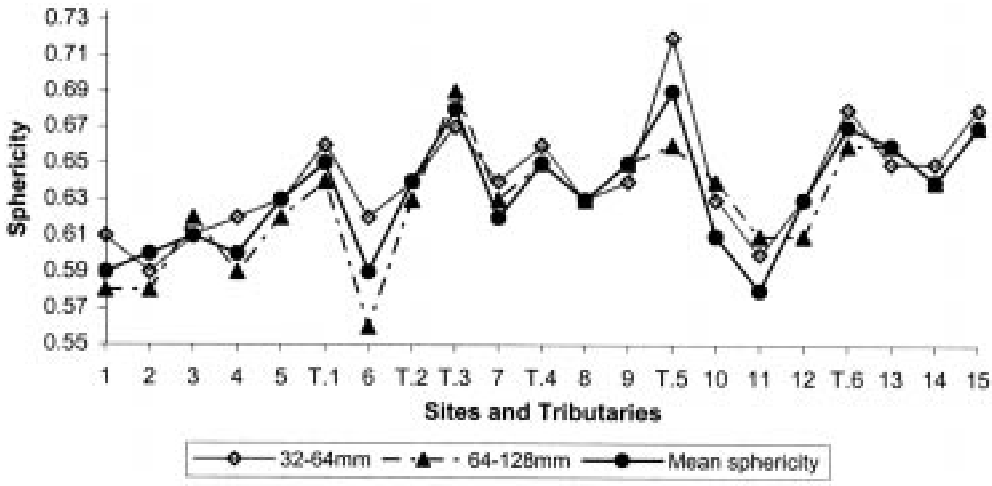

Figure 7. Downstream changes in mean sphericity of all size categories and the two clast size categories separately.

Şekil 7. Akarsu yatağı boyunca yatak malzemesinin ortalama küreselliğinin tüm tane boyutları için değişimi ve küreselliğin her tane boyutu grubu için ayrı ayrı değişimi.

and nature of material supply areas, (b) bedrock structure, (c) tributary junctions, the processes of abrasion, breakage and sorting (Knighton, 1982). The first influences the form and regularity of downstream change, particularly of clast size. The main effect of bedrock structure is on clast shape. The processes of abrasion and sorting generally control the reduction in the size of bed material and change in shape with distance downstream. The influence of tributary inflow on the bed material characteristics of the main stream will vary with the difference in the amount and composition of the two sediment loads, (which in turn will depend on their origin and history) and on the relative and absolute size of the tributary at the point of entry.

Many studies (e.g. Krumbein, 1942; Sneed and Folk, 1958; Mills, 1979; Knighton, 1982, Ferguson et al., 1998) have shown that roundness increases and clast size decreases in a downstream direction along many rivers. The Cwm Treweryn stream, however, does not conform this simple downstream pattern, instead showing irregular and complex changes in both size and shape along the channel. The reasons for this are now discussed.

Size

In most cases fluvial deposits are well sorted along a river channel. But in the Cwm Treweryn channel this phenomenon is not observed. The poor sorting along the study river occurs mainly because the terrain has been glaciated and provides a ready supply of unsorted glacial boulders and gravels, along much of its course. The natural tendency for sorting by the river is repeatedly interrupted therefore by fresh inputs of unsorted material.

At all 15 sites samples were characterised by a wide range of size fractions (from 32-192 mm), showing an irregular downstream changes and thus poor sorting (see Figure 3). Possible reasons may be attributed to the following factors:

First, between Sites 4 and 8 there are many cobbles and boulders that could have come mostly from the channel banks and the rocky bed and are generally resident and probably do not form part of the active bedload (see Figure 4). Peak flows in the relatively small channel at these sites may be insufficient to transport such coarse material, although channel gradient is high.

From Site 8 to the confluence with Tributary 5 and Site 10, channel gradient decreases sharply and channel width increases (see Figure 2) and material is somewhat better sorted compared with further upstream. Boulders of >128 mm size are much less frequent than upstream, only 1-3 % at Sites 9 and 10. The decline in boulder material may be linked to both to this decline in gradient and to the absence of large boulders in the bank material. Most of the bank material consists of finer material of 32-128 mm size.

Below the point where Tributary 5 joins the main channel (between Sites 9 and 10), 32-64 mm and 64-128 mm categories are of equal percentage, suggesting that Tributary 5 is transporting smaller size material than the main channel. This is indeed the case as the graph for Tributary 5 shows. On the other hand the bank material in this section also generally consists of small size clasts and this may also help to account for the lower percentage of >128 mm size material.

The increase in size from site 12 to 14 might be due to inputs of flat cobbles and boulders from the stony channel bed, but more important is probably fresh inputs of very large boulders as a result of bank erosion of glacial deposits as at Site 13. Below Site 14, the absence of inputs of fresh bank material may result in the better sorting at Site 15.

It is useful to compare the Cwm Treweryn results with those along a 20 km stretch of the Neo River in north Derbyshire, England (Knighton, 1982). Along the Neo, although there was a distinct downstream decrease of mean grain size of sandstone bedload, shale clasts did not exhibit the same pattern. Because shale outcrops at the various points along the stream, the frequent inputs of fresh material produce a great irregularity in size distribution within that group, whereas the sandstone clasts were largely supplied from headwater sources and thus modified were able to progressively downstream in shape and size once it has left that zone. The Cwm Treweryn shows similar traits to the shale component of the Noe's bedload in that there is also a discontinuous input of fresh Old Red Sandstone material at points along the channel (see Figure 4). A second factor is stream length. Knighton observed the downstream changes in size within 20 km, whereas the total length of the Cwm Treweryn channel is only 6 km which may be insignificant to accomplish a significant decrease in size and in particular for sorting mechanisms to operate effectively. Knighton (1980) found that the rate at which mean grain size decreases downstream varies between streams and is directly related to stream length and lithology, suggesting that the effectiveness of sorting and abrasion can be considered realistically in terms of a distance variable.

Shape

The dominance of disc shape in the larger (64-128 mm and >128 mm) clast size grades is mainly caused by structural and lithologic characteristics of the Old Red Sandstone and the fresh inputs of this material at points along the channel. The sandstone in the Cwm Treweryn Catchment possesses a tabular bedding structure resulting in well-defined planes of weakness in a given rock mass. The sandstones are also jointed, fractured and laminated. All these factors, with the tabular bedding being dominant, result in flat pieces of sandstone when they are released to the stream channel system. These sharp edges of tabular pieces are then smoothed to make them the typical disc-shaped clasts of the bedload. The fact that blades are the second most frequent shape can also be linked to the same lithological factor: the more linear rock fragments becoming blades. The continued dominance of discs and to a much lesser extent blade-shaped clasts downstream in the >64 mm fractions may also indicate either (i) selective transport by shape sorting, or (ii) fresh inputs of tabular material along the channel. The latter is thought more likely as there is considerable evidence of bank inputs along the course of the Cwm Treweryn.

The overall dominance of discs along the channel is simply a result of the dominance of the larger size grades, as in the small pebble category (32-64 mm) the combined frequency of blades and rods exceeds the frequency of discs at every site (see Figure 5). The reasons for the lower frequency of discs of 32-64 mm size is unclear. A possible reason might be that smaller clasts are in part a result of breakage (rather than abrasion) of larger flat clasts and thus possess an automatically less flat form.

It is noticeable that as clast size declines in the middle sites of the Cwm Treweryn, the percentage of disc-shaped clasts also declines slightly (see Figure 5). Again, this is at least in part caused by a decline in the frequency of larger (>64 mm) clasts and an increase in frequency of the 32-64 mm clast category, in which discs are less frequent (see Figure 5). In the lower section however, the frequency of >128 mm clasts and the mean size of clasts increases again, thus accounting for a renewed increase in the percentage frequency of disc and blade-shaped clasts.

The increase in frequency of rods and spheres within the smaller (32-64, 64-128) size fractions downstream (see Figure 5) might be in part a result of their selective transportation. With the decline in channel gradient, stream power may favour transport of clasts that roll more easily, namely rods and spheres. As some of the earlier studies proved (e.g. Krumbein, 1941; Carling et al., 1992; Schmidt and Gintz, 1995) for similar sized clasts, rods and spheres move more frequently than flat shaped clasts, although rods and spheres also tend to settle more rapidly as channel gradient or discharge falls (Sneed and Folk, 1958).

Roundness

Mean roundness of all clasts increases from 116 to 235 between Sites 1 and 9, falls sharply at Sites 10-12 and it tends to rise again between Sites 13 and 15 (see Figure 6.a), but mean roundness of individual size categories of clast shows little change with distance downstream (see Figure 6b).

Many authors (e.g. Wentworth, 1922; Kuenen, 1956) have indicated that larger clasts are more easily rounded than smaller ones, in other words that roundness increases with clast size. In contrast in the Cwm Treweryn there is a generally negative linear relationship between clast size and roundness (see Figure 6b). In general, there tends to be an inverse relation between mean roundness and clast mean size.

This might be attributed to the higher rolling velocity and more frequent transport of smaller clasts in the Cwm Treweryn stream. Also most of the >128 mm size grade cobble and boulders are 'residual' and are either rarely or never transported.

At Sites 1-4, which is near the watershed boundary, roundness is lowest (112-116) indicating the dominance of angular fresh material from the channel, its banks and the valley slopes. The progressive increase in roundness downstream of Site 4 to 236 at Site 9 probably reflects abrasion with transport along the channel, although the roundness decrease at Site 6 and Tributary 2 may be influx of large angular cobbles and boulders in that reach. The increase in roundness at Sites 8, and 9 and Tributary 5 can also be linked to a decline in percentage and size of cobbles which are left upstream as channel gradient decreases markedly (see Figure 6).

Although Sites 9 and 10 are very close (200 m), roundness decreases sharply between two sites. A possible explanation for this decrease may be linked to the increase in mean flatness at Site 10, which may in turn be a result of selective deposition associated with the development of pool-riffle sequences at Site 10, whereas the reach of Site 9 is straight and shallow and pool-riffles are poorly developed.

This decline in roundness intensifies at Sites 11 and 12 (see Figure 6a), where it appears to be associated with increasing size and flatness of bedload and again inputs of fresh material from the banks. Also, at Site 12 most materials were sampled from a pool section, where size and flatness of material were higher than at bar and riffle sections. The increasing roundness at Sites 13-15 might be linked in part to the input from Tributary 6 and in part to the operation of sorting and abrasion processes in the absence of significant fresh inputs within these lowermost reaches.

Thus the overall increase in roundness along the Cwm Treweryn is relatively small due to discontinuous supply of fresh materials from the channel banks, valley side slope and from the bedrock along the channel. It can also therefore be attributed to the short length (6 km) of the channel, which may be insufficient for significant rounding by abrasion to override the impact of fresh inputs.

In studies that recorded larger increases in roundness, much longer river stretches were studied; thus the studies of Plumley (1948), Ouma (1967), Hollerman (1971), Gregory and Cullingford (1974), Geode (1975), Mills (1979), and Knighton (1982) were all over stretches of 20-100 km. Only the study of Hoverman and Poser (1951) of sandstones clasts over a similarly short (5 km) stretch of river in the Harz Mountains in Germany recorded findings similar to the Cwm Treweryn.

Another possible contributory explanation of the irregular downstream change in roundness for the Cwm Treweryn may be the high resistance of the Old Red Sandstone bed material to abrasion. As Sneed and Folk, (1958) remarked, most workers choose the softer rock types for their studies because of their more rapid abrasional response to transport. In other words the lithologic character of the bed material strongly influences the rate at which roundness increases with distance downstream. Many investigators have shown (e.g. Sneed and Folk, 1958; Kuenen, 1956, Mills, 1979) that downstream roundness tends to increase rapidly for limestone, least rapidly for quartz and quartzite, and at intermediate rates for other lithologies. Old Red Sandstone is highly resistant and therefore may increase in roundness relatively slowly with distance downstream.

Sphericity

Sphericity is a complex function of lithology, pebble size, and distance of transport (Sneed and Folk, 1958). In the Cwm Treweryn, sphericity increases between Sites 1 and 9 up to the junction with Tributary 5 (see Figure 7). As with roundness a possible explanation of this may be (a) progressive abrasion of clasts breakage with transport downstream and (b) a rapid decline in percentage of cobbles and boulders which reflects in part the action of sorting processes in that the cobble and boulder clasts tends to remain as residual lag deposits upstream and (c) a general decline in mean clast size as channel gradient declines within the stretch (see Figure 7).

Below Tributary 1 downstream changes of both mean sphericity of all clasts and of the two size grades are irregular. This may be a result of irregular changes of clast size in the same direction due to contribution of fresh material from the banks and channel bed.
Some earlier studies (e.g. Wentworth, 1922; Sneed and Folk, 1958) showed that sphericity increases with distance downstream, although the rate and scale of increases varied from one study to another. Sneed and Folk, (1958) point out that sphericity depends most importantly on lithology (via its influence on initial clast form and subsequent abrasion or breakage properties), is strongly a function of size and distance downstream, but is little affected by selective sorting. For sphericity they found that the second most important factor was distance of transport, whereas for roundness the order was reversed.

In the Cwm Treweryn sphericity values are considered to be low for four reasons. First, the bedload consists of Devonian Sandstones which result in flat, disc-shaped (and to a lesser extent blade-shaped) clasts of inherently low sphericity. Second, the river course (6 km) is short compared with most other studies; for example Sneed and Folk (1958) studied a 435 km stretch of the Colorado River, Unrug (1957) more than 57 km and Krumbein (1941) 32 km. Third, the sandstone is hard and resistant to abrasion, whereas many investigators chose limestone for their study, because limestone is very soft and it reaches the maximum possible river sphericity value within a few kilometres. The fourth contributory reason is the discontinuous inputs of fresh material from the banks and valley slopes along the entire channel.

Sneed and Folk (1958) also pointed out that clast size has an important effect on sphericity. They found that, near the source, clasts of all sizes were about the same sphericity but that, as pebbles are carried further away, the larger ones become less spherical and small ones more spherical. In the Cwm Treweryn, however, there is no significant difference in sphericity with clast size (32-64 versus 64-128 mm) at any point along the stream (see Figure 7). This again may reflect the shortness of the course of the Cwm Treweryn, the resistant sandstone lithology and the fresh inputs along the channel.

CONCLUSIONS

This study demonstrated that, when compared to other studies, downstream changes in bed material size and shape characteristics are irregular and also rather complex due to the combined effect of following factors:

1. In terms of size characteristics, bed material at all 21 sites were characterised by a wide range of size fractions (32-192 mm) and hence poor sorting. A tendency towards better sorting was disturbed by fresh inputs of large angular Old Red Sandstone material in the middle reaches.
2. Disc-shaped clasts are dominant in the larger clasts categories (64-128 mm and >128 mm) along the entire channel with blades the second most frequent shape. The two main reasons are considered to be (a) structural and lithological characteristics of the Old Red Sandstone, which produces flat, tabular clasts and (b) fresh inputs of large clasts at points along the channel. In the small pebble category (32-64), discs are much less frequent with rods and spheres of increased frequency.
3. Roundness and sphericity showed a pattern of first an increase, then a decline and finally a renewed increase along the course of the Cwm Treweryn. This pattern is linked to inputs of fresh, large angular material in the middle reaches disrupting the impact of a downstream decline in size. As both roundness and sphericity values, especially of larger clasts, are low; this is also linked to the flat initial clast form and resistance to wear imparted by the sandstone lithology as well as the short course of the Cwm Treweryn and the fresh inputs along its course.
4. In terms of downstream changes in size and shape variables, patterns along the Cwm Treweryn were unlike those generally reported in previous studies. The main reasons for the absence of simple downstream increases in roundness and sphericity and reductions in flatness and size were considered to be (1) the discontinuous inputs of fresh angular material from bank erosion of unconsolidated glacial and periglacial deposits along the channel course, (2) the comparatively short (6 km) length of channel that was studied, (3) the resistant Old Red Sandstone lithology of the clasts reducing rates of abrasion, and (4) tributary inputs along the channel course.

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