Sediment storage, bed fabric and particles features of two mountain streams at Plynlimon (mid-Wales)

Paolo Billi

University of Florence

May 1987

Report No. 97

Abstract

The report presents the results of a study into the effect of sediment storage, bed fabric and particle characteristics on bedload transport rate and its short term variations, in two mountain streams. Grain size distribution and particle shape distribution curves are similar for both streams. Variations in bedload yield seem to depend largely on differences in channel sediment storage and release.

Preface

This paper is the first outcome of a two months research visit made by the author to the Plynlimon catchments monitored by the Institute of Hydrology. The visit was financially supported by the British Council and by the University of Florence. All the facilities used were provided by the Institute of Hydrology.

Due to the scarcity of available time, the author's attention was concerned with two small mountain streams representative of different physiographic and vegetation conditions. The chosen streams belong to the upstream catchments of the Wye and Severn rivers respectively where the Institute of Hydrology has undertaken long-term studies of basin hydrology and sediment yield.

The report is concerned with the bedforms and sediment characteristics of such streams and their relations with sediment transport and its variations.

The author would like to thank all the staff at Plynlimon and particularly Mr John Smart. The author is grateful to the Director of the Institute of Hydrology, Dr James S G McCulloch, for permission to make the visit.

Contents

1. Introduction

The rate of bedload transport of alluvial channels depends on many factors most of which are not very well known and difficult to measure in the field.

A lot of laboratory flume experiments have been carried out in order to investigate the relations among the parameters involved in bedload transport processes and many equations have been proposed to predict the quantity of bed material moved during a flood. The suggested hydraulic formulae can be rarely verified in the field because of the difficulty of measuring bedload transport of natural streams. Unfortunately, the application of such equations to rivers, where reliable data on sediment transport are available, show that the theoretical approach to sediment transport is often unsuccessful. In general, factors such as the sediment storage or the bed fabric are not considered in the hydraulic formulae, but they can probably account for the large and commonly unpredicted variations of bedload transport rate which are typical of coarse-grained mountain streams.

The aim of the present study was to stress the effect, if any, of sediment storage, bed fabric and particle characteristics on bedload transport rate and its short-term variations.

The Afon Cyff (Wye basin) and the Nant Tanllwyth (Severn basin) match very well the requirements of such research as their physiography has been studied in detail (Newson, 1976; Newson and Harrison, 1978) and many hydrological parameters have been monitored for a long time by the Institute of Hydrology. Both streams are equipped with a bed trap by which integrated measurements of bedload yield are possible by flood or during different stages of a single flood (Newson, 1980).

2. Physiography and general setting

The general physiography of the Plynlimon catchments has been described by Newson (1976); only a brief outline of the main features of the studied streams is reported here.

The Cyff and the Tanllwyth are two small mountain streams which belong to the Wye and Severn headwaters respectively.

The catchment of the Cyff has an area of 3.776 sq km (Fig. 1a) and it is rather elongated in shape with an elongation ratio of 0.35 and a circularity ratio of 0.29. The maximum elevation is 698, the lower 355 m a.s.l. The drainage density, measured on a 1:10,000 topographic map (excluding artificial drains), is 5.8 km/km^2.

The Tanllwyth (Fig. 1b) has instead a smaller basin of only 0.931 sq km but its shape is similar to that of the Cyff with an elongation ratio of 0.34 and a circularity ratio of 0.35. Its maximum elevation is 549 m a.s.l. and the lower 350 m a.s.l., whereas the drainage density is 6.7 km/km^2.

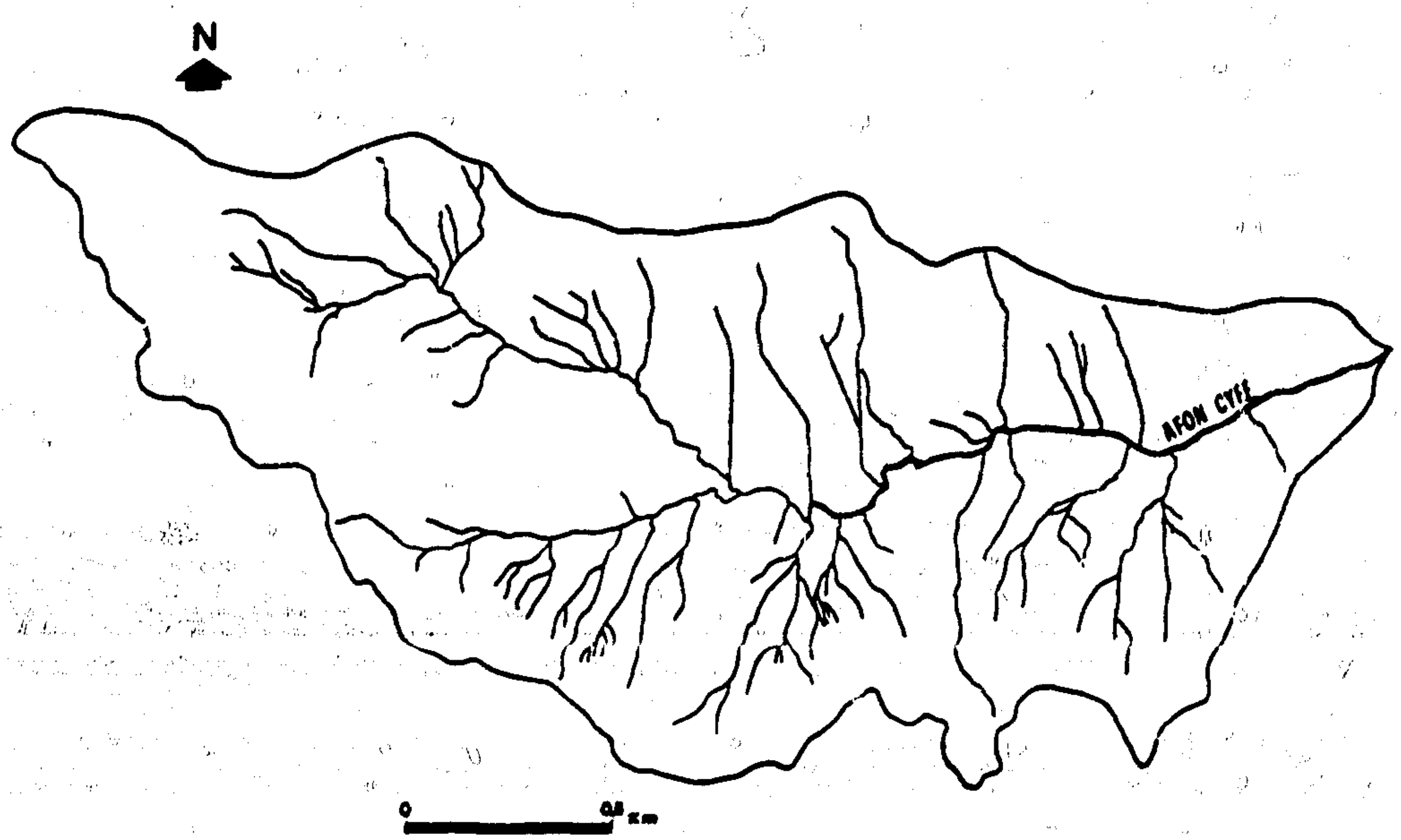


Fig. 1 (a) the Afon Cyff

Both catchments are mostly covered by peaty soils but their vegetation is quite different and it probably makes the most important distinction between them. The Cyff has an almost natural vegetation cover consisting mainly of natural or partly reseeded grassland whilst the Tanllwyth is characterized by artificial coniferous afforestation.

According to the data reported by Newson (1976) for the period 1968-1974 the annual rainfall ranges from 1888.9 to 2501.2 mm with a yearly mean of 2232 mm and the total number of rain days (0.2 mm and over) ranges from 210 to 257 with a mean value of 232.

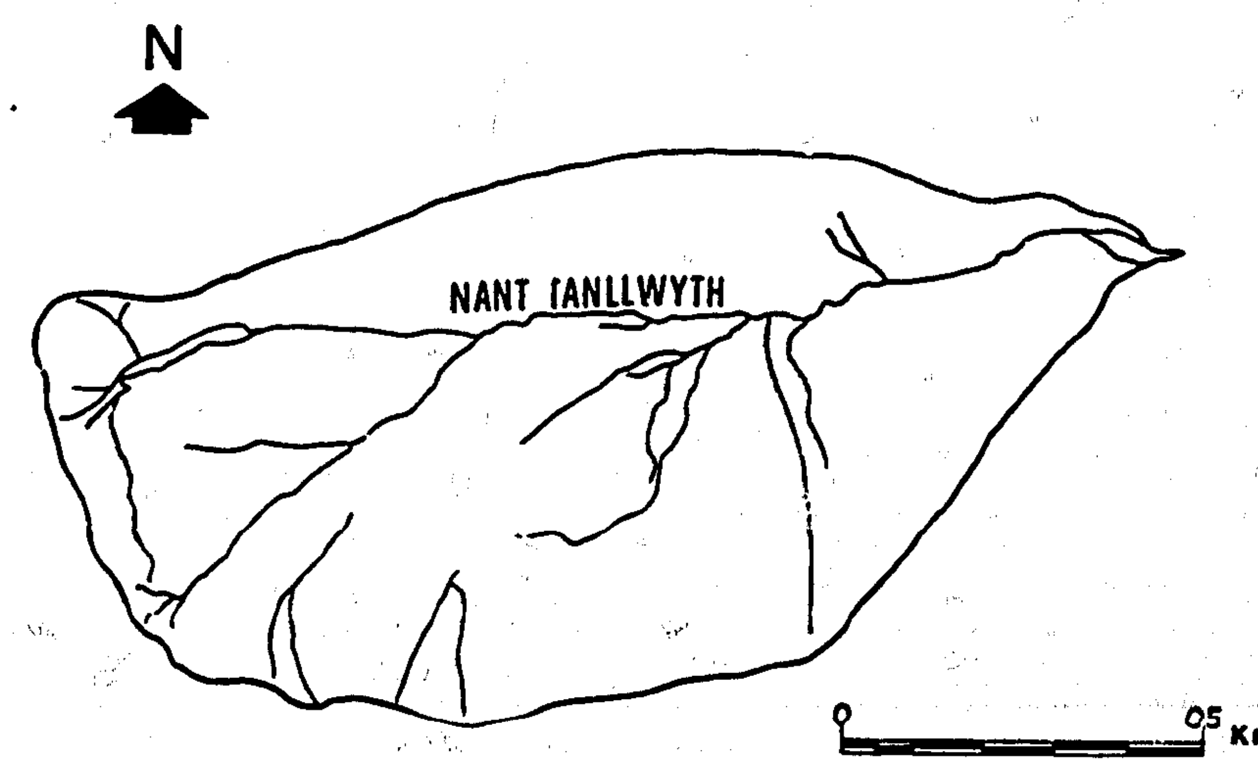


Fig. 1 (b) the Nant Tanllwyth.

2.1 Channel reaches classification

Both the Cyff and the Tanllwyth are steep mountain streams with the channels characterized by the occurrence of wide bedrock outcrops. Both channels consist of bedrock-lined reaches separating sediment-lined reaches of variable length.

The outcropping of bedrock causes a definite increase in local gradient and a tumbling flow is common bedrock reaches even at low discharges. Consequently, sedimentation of large particles does not occur in such reaches which are more likely to supply coarse bed material by bedrock fracture during high floods.

In sediment-lined reaches the flow is generally subcritical at low discharge, but can become supercritical (Froude number > 1) during a flood. The bed of such a reach commonly consists entirely of coarse poorly-sorted material ranging in size from large boulders (up to 500 mm in mean diameter) to fine grains.

For practical purposes, since the study was mostly on the sediment, a classification and mapping of the different types of reaches was made. It was based solely on the field survey of the two main streams whereas their tributaries were not considered. The classification adopted is a little different from that suggested by Newson and Harrison (1978) for the same streams.

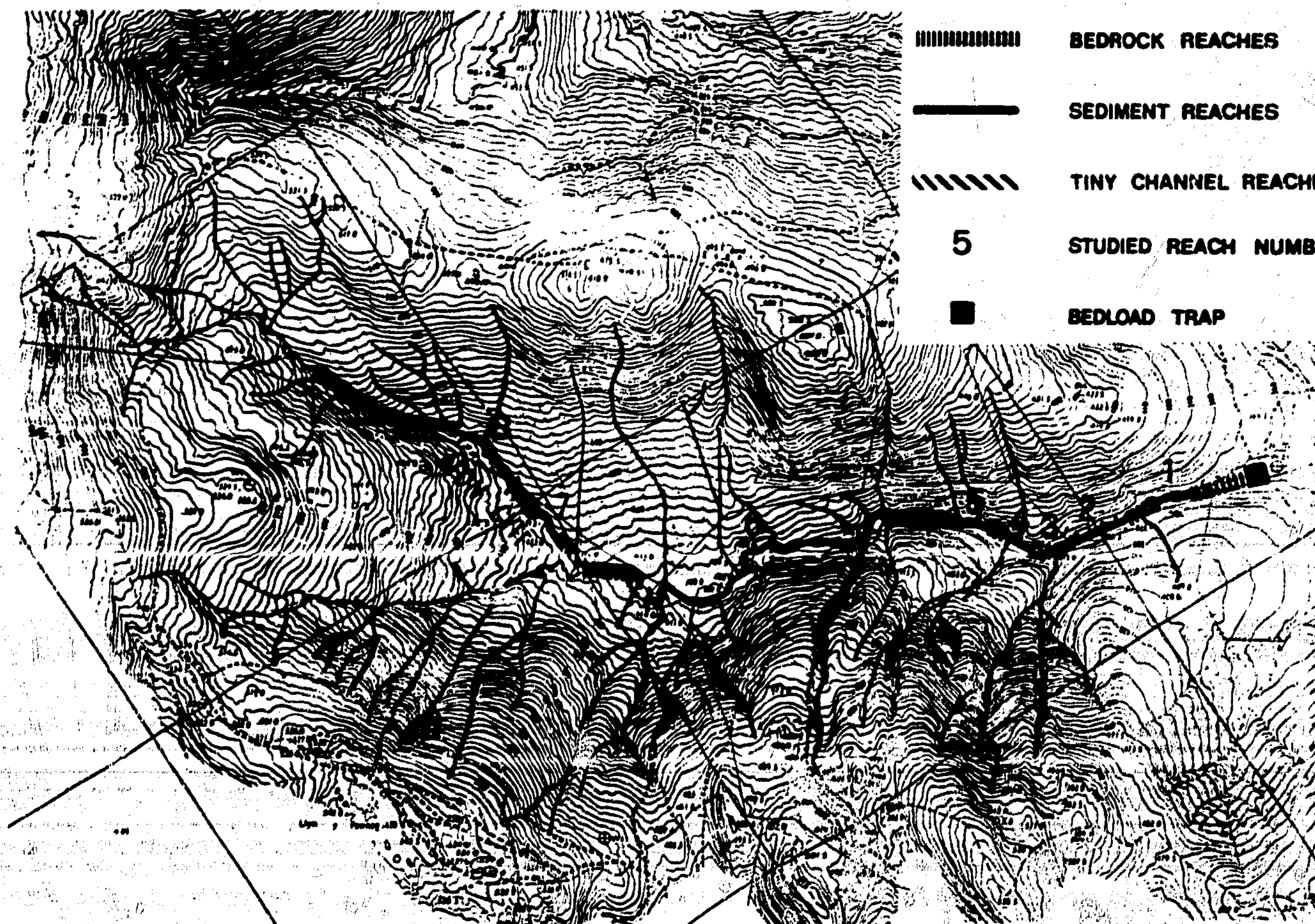


Fig.2 Reach classification: (a) the Cyff.

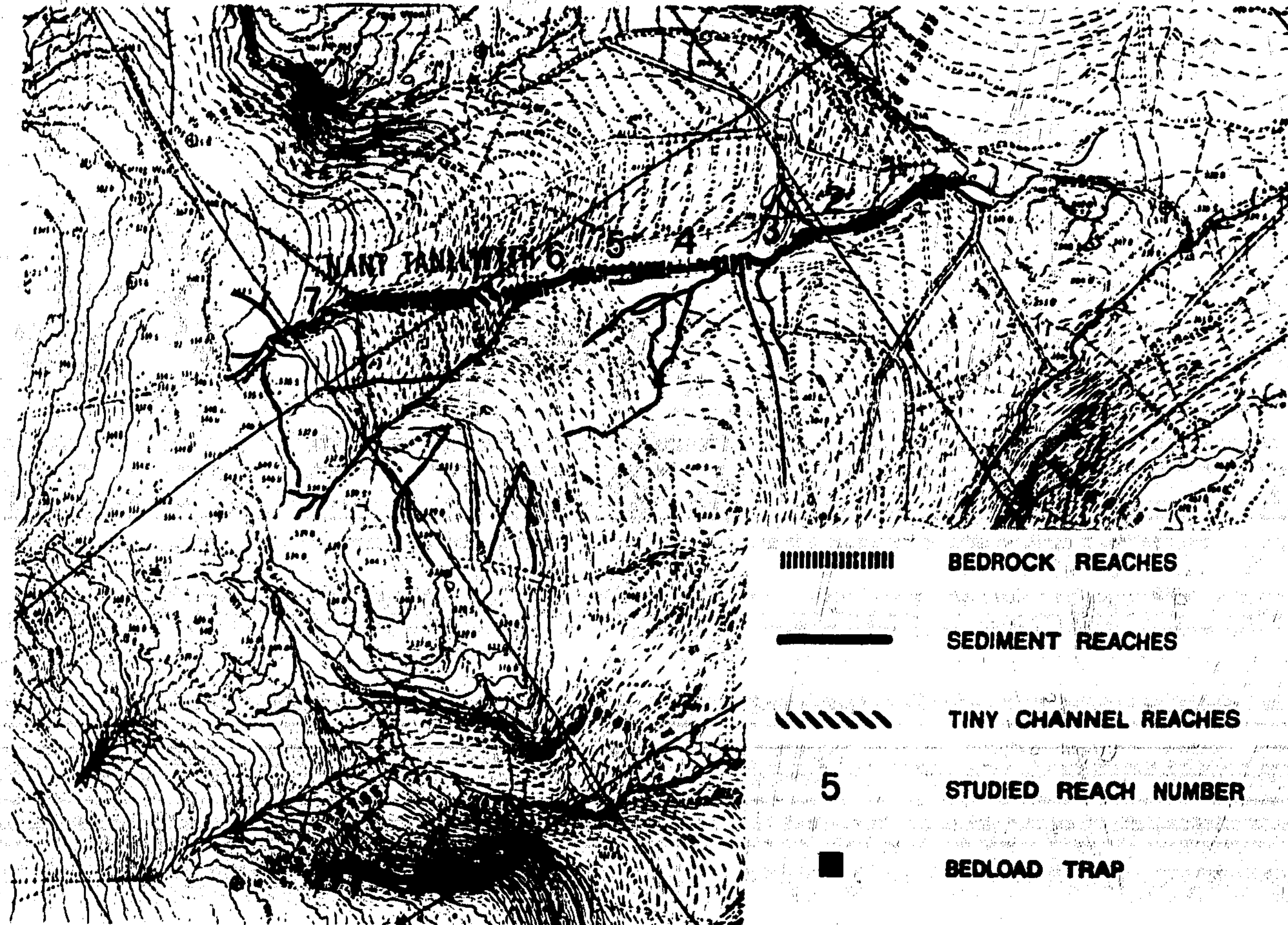


Fig.2 Reach classification: (b) the Tanllwyth.

Only three main types of reach were recognized; they are :

Bedrock reaches. The stream bed consists entirely of bedrock outcrops.

Sediment reaches. The stream bed consists entirely of boulders and pebbles and it is several times wider than the largest particle.

Tiny reaches. The stream bed consists entirely of sediment but its width is of the same order of magnitude as the mean diameter of the largest particles.

Each reach was considered for mapping only if its length was larger than the width of the stream bed at that particular site. Too short reaches were included in the longer ones.

From this classification eight and seven sediment reaches result respectively for the Cyff and the Tanllwyth (Fig. 2). These 15 reaches were then taken as study reaches.

2.2 Channel morphology

The morphology of the Cyff and the Tanllwyth is consistent with that of a straight mountain stream. The channel path is commonly straight and only a few bends occur. They are generally due to local effects such as those induced by the oblique strike of the bedrock bedding, by the occurrence of a large collapsed bank deviating the flow towards the opposite bank or by a tree trunk fallen across the channel. In the studied reaches, none of the bends seem to be due to the interaction between the sediment and the flow.

Both streams have a small alluvial plain in their very downstream reaches. More commonly the channels are entirely eroded into the bedrock and the banks consist of colluvial deposits. In the higher reaches the banks may be cut into glacial tills (Newson, 1978).

For the surveyed sediment reaches the following site morphologies were recognized:

Riffles They occur as a local increase of the stream bed gradient and have rapid shallow flow with a steep water surface. In the studied streams riffles are not necessarily composed of the coarser sediment and they are more common and well developed on longer reaches where bedrock control is scarce. Only very few riffle and pool sequences were observed; riffles are spaced about 2-4 channel widths which is less than that which is generally reported in literature (5-7) for purely alluvial channels.

Pools Pools are deeper than riffles and water flows more slowly with a gentle surface slope. Their bed is in general composed of finer material. In the studied reaches pools with a coarse lag were also observed.

Stepped pools Stepped pools are a typical features of steep mountain streams with very coarse bed material. They are characterized by a staircase like appearance (Whittaker and Davies, 1982); water flows over groups of boulders arranged in a straight or curved line across the channel and plunges into the downstream pool which may be relatively deep and dissipate the flow energy. The steps are generally made of the largest particles available from the bed. Their size may be of the same order as the channel width and during low flow they can locally overhang the water. The step spacing/channel width ratio ranges from 0.5 to 1.0. The value of 1 is considered here as an upper limit over which the site is classified as a pool. In the studied reaches, stepped pools consisting of up to ten consecutive step-pool systems were observed.

Lateral bars They are rather uncommon on the Cyff and the Tanllwyth and represent the only bar type observed. Any accumulation of sediment whose width was at least of the same order as the width of the channel was identified as a lateral bar. Less laterally extensive deposits were considered as parts of the stream bed emerging at low flow. In the studied streams the lateral bars are generally elongated and diamond-shaped and always attached to one of the banks. They may be originated by common accretionary processes as well as in purely alluvial channels or may be the product of deposition in the wake of a small bedrock prominence. Sometimes the material coming from bank failure is not completely eroded (probably because the collapse occurred while the flow was waning), then, during subsequent floods it may be reworked and thus gives way to a new lateral bar. The first type of lateral bar shows fabric features and an areal distribution of particle size consistent with the downstream accretion of the bar, whereas the second type generally does not as it is largely affected by locally-induced turbulence.

Table 1 shows the frequency of the different site morphology surveyed for the studied streams whereas on Table 2 the numbers of the boulder steps counted for each reach (see Appendix A for details) are reported.

Table 1

	Cyff	Tanllwyth
Sites	n.	n.
Riffles	17	3
Pools	19	15
Stepped pools	17	17
Side bars	5	1

Table 2

Number of Boulder Steps

	Cyff	Tanllwyth
Reach 1	6	9
Reach 2	13	10
Reach 3	3	13
Reach 4	10	22
Reach 5	4	6
Reach 6	50	8
Reach 7	12	4
Reach 8	12	-
Total	110	72

In Table 1 a remarkable difference in the number of riffle sites between the Cyff and the Tanllwyth can be seen. The lack of riffles in the Tanllwyth may be explained as being due to the strong control exerted by the bedrock on the stream morphology, the shortness of the sediment reaches and the high gradient. Moreover, the residence time of the bed sediment in the channel may be so brief or affected by particular conditions of local storage that the organization of the bed in riffle and pool sequences cannot be easily achieved.

It seems that no relation exists between the number of boulder steps and the reach length. Neither the up or downstream location nor the slope of the sediment reaches seem to have any effect on the boulder steps number. It was instead observed in the field that the boulder steps spacing generally decreases as the average gradient of the stream bed increases.

2.3 Channel geometry

Several cross-sections were measured in the sediment reaches of the Cyff and the Tanllwyth. The cross-sections were spaced from 5 to 10 m, depending on the reach length, and correspond to the bankfull discharge. For each section the mean bankfull depth was obtained by averaging the depth values measured on verticals spaced 20 cm (see Appendix A for details). The mean width and depth averaged on the whole reach length, are reported on Table 3.

The data of Table 3 show there is no particular trend in the width and depth of both streams. This depends again on the strong control the bedrock exerts on the channel geometry so that upstream reaches may be broader than downstream ones.

Table 3

Reach	Cyff Mean Width (m)	Cyff Mean Depth (m)	Tanllwyth Mean Width (m)	Tanllwyth Mean Depth (m)
1	3.10	0.74	3.10	0.65
2	4.10	0.61	2.20	0.72
3	6.20	0.84	2.20	0.61
4	3.60	0.51	2.40	0.53
5	5.50	0.83	2.20	0.49
6	-	-	3.00	0.50

3. Sediment storage

Newson (1980) reports large variations of bedload yield for the Cyff and the Tanllwyth. What is more interesting is that remarkable differences were observed at approximately the same flow rate. The causes are complex and probably different from those quoted for purely alluvial streams.

In the present study two of the possible causes were investigated. They are sediment storage and the bed fabric.

The effects of the sediment storage (the bed fabric is discussed in the following chapters) on bedload yield could not be monitored during the research visit because of its brevity. Fortunately, as the Cyff and the Tanllwyth are rather short and absolutely untouched, the overall conditions of sediment storage can be conveniently observed.

In the studied reaches the bed sediment occurred in different quantities. A few reaches were overloaded with sediment whereas in others, even similar in size and gradient, sediment was scarce. This irregularity in sediment accumulation may depend on different causes. The sediment can be trapped by a narrowing of the channel due to the failure of a bank, by the local deposition of an exceptionally big boulder step that hinders the movement of the bed material or by the accumulation of vegetation debris forming a small weir across the channel. The volume of the bed sediment yielded during a flood obviously may depend also on the persistence of the conditions that caused the sediment storage. If for example during an ordinary flood the vegetation dam collapses an unusual volume of sediment can be released and the bedload transport may be higher than expected.

However, some reaches showed either abundance or scarcity of sediment independently of visible local causes. The theory of kinematic waves (Langbein and Leopold, 1968) could be a possible explanation for that. In order to verify the application of this theory several photographs of the studied reaches were taken. By another photographic survey, after an appropriate span of time (1-2 years depending on the frequency and magnitude of the floods), it should be possible to observe the downstream progress of actual sediment waves.

4. Bed sediment survey

A few authors believe that sediment fabric and bedforms play an important role in the bedload transport processes of gravel-bed rivers (Laronne and Carson, 1976; Brayshaw et al., 1983; Brayshaw, 1984; Reid and Frostick, 1984; Reid et al., 1985). According to these authors such factors may account for the variations of bedload transport rate and for its poor correlation with flow rate.

Unfortunately, very few data on this topic are available for steep mountain streams.

Secondly, a question arises about the effect of the bedrock control on the bed fabric, the occurrence of bedforms and the distribution of the particle size and shape.

During the research visit it was not possible to monitor the effect, if any, of such features on sediment transport. They were then surveyed in the field aiming to infer their influence through the frequency and the scale of their occurrence on the studied reaches.

4.1 Methodology

Every sediment reach of the Cyff and the Tanllwyth was subdivided into different shorter sites which were identified according to the morphological classification described in Chapter 2.2

The bed fabric and bedforms occurring at each site were surveyed by direct observation of the stream bed.

For a more objective procedure of field data gathering, a survey form, consisting of fixed ranges of frequency and a bedform classification (see the following chapters for specific information), was prepared. Fortunately the water clarity always allowed a detailed examination of the whole bed and only for a few sites of reach 6, 7 and 8 of the Afon Cyff, was the survey of bed fabric and bedforms not completed because of a rather thick algal drape covering the stream bed.

4.2 Bed fabric

The term 'bed fabric' is used here in its more general sense as it is concerned with the overall arrangement of the bed particles.

Three main aspects were investigated: the particle-interlocking, imbrication and the bed armouring. Only a qualitative description of these important features of the stream bed is given in the following chapters as the scarcity of time did not allow a detailed analysis and measurement of such parameters. For steep mountain streams data on these features are unfortunately very scarce or lacking

entirely. Thus, any observation, even qualitative, may be useful in understanding the relation between bed fabric and bedload transport in coarse-grained poorly-sorted streams characterized by a strong bedrock control.

The observations made on the Cyff and the Tanllwyth refer just to a specific span of time during which no large flood occurred. Repeating such observations after one or more bankfull floods wou[illegible]t a study of bed fabric evolution in time and space and its relation to [illegible]draulic parameters.

4.2.1 Particle interlocking

The packing of the bed material was noted to display different modes which nevertheless can occur jointly. The bed particles may rest in a non-imbricated position on their maximum projection plane and be juxtaposed with several contact points. This mostly happens if the sediment sorting is good. In case of very poorly-sorted sediment, the finer gravel may interpose among the larger cobbles filling any interstice resulting from their imperfect contact. This kind of particle arrangement gives way to an 'open pane-bed' (this term is borrowed from Brayshaw (1985) who used it in a different context and regardless of its definition, but the bed fabric showed in his Figure 2 well matches the above description).

The bed at a few sites and the surface of most of the lateral bars consisted instead of loose non-imbricated particles which displayed a random orientation of their longest axis and only occasional contacts. On such a bed, named here as 'loose-particles bed', the pebbles can be easily entrained as they are almost entirely exposed to the flow and the effect of the factors opposing their incipient motion is reduced to a minimum. Bedload transport rate can then be higher on a loose-particles bed than on an open plane-bed where the mobility of clasts of any size is lower, since their interlocking prevents them from being easily removed by the flow.

On the Cyff and the Tanllwyth these two modes of particle-interlocking seem to occur regardless of sediment sorting and grain-size distribution. Locally loose particles as well as imbricated pebbles may be clearly located on an open plane-bed. Imbrication is a very well known form of particle-interlocking. It is the most stable bed configuration as it results from the hydrodynamic forces and those opposing the motion acting jointly in pressing the imbricated pebble down onto the bed. On the studied streams imbrication was not widely developed (see the following chapter for more details), and the reasons why different modes of particle-interlocking occur are not clear at present. However, further investigation is needed on this subject as it too could tell us much about the variations of bedload transport observed on gravel-bed rivers.

4.2.2 Pebble imbrication

For each site of the surveyed sediment reaches imbrication was evaluated as the percentage of the bed surface covered by well-imbricated pebbles.

On average only one third of the Tanllwyth stream bed was taken up by well-imbricated particles and no site showed an imbrication level more than 50%. On the Cyff, instead, about one half of the bed pebbles were well imbricated and a few sites displayed imbrication of the whole bed.

It is difficult to explain this difference in the imbrication degree of the two streams. The Cyff has a larger catchment and a lesser gradient than the Tanllwyth. Floods have then a longer duration and thus the pebbles are more likely to be deposited in an imbricated and consequently more stable position.

On both streams most of the pebbles dip upstream at an angle widely variable from 0 to 90°, whereas the orientation of the longest axis is generally perpendicular to the main flow direction. Locally, a few elongated pebbles are oriented with their longest axis parallel to the flow. This may depend on a very high flow velocity or on local turbulence effects induced by large boulders and other rough elements of the bed.

4.2.3 Bed armouring

Both the Cyff and the Tanllwyth showed a distinctive bed armouring. Only in very small parts of a few sites was the bed armouring not observed. In all these cases some local effect of turbulence due to the upstream occurrence of a very big boulder or the remains of a collapsed bank was involved.

Armouring is then a very common process on steep mountain streams, where bedrock control is strong, and represents their most evident similarity with purely alluvial rivers.

As reported in the following chapters, several sediment samples were taken from the armoured layer of the studied streams and grain-size analysis was made. No data on the grain-size distribution of the sub-surface material could be gathered. If in the future more information becomes available on the size characteristics of the sub-surface material, by comparing the grain-size distributions of the armoured and sub-armoured layers with that of the sediment collected by the bedload traps on the Cyff and the Tanllwyth it should be possible to shed some more light on the problem of bed armouring and transport.

4.3 Bedforms

The stream beds of the Cyff and the Tanllwyth are distinctively armoured and consist of coarse-grained poorly-sorted gravel. On the bed surface finer sediment of sand size or less is almost absent, being washed away during floods. Bedforms are consequently made up mostly by coarse material.

Only very few types of small-scale gravel bedforms have been described in the literature; they are: dunes, antidunes, pebble clusters and transverse ribs.

Neither dunes nor antidunes were observed on the studied stream beds. Pebble clusters and transverse ribs, instead, occur quite commonly. Attention was paid to them particularly in order to investigate their influence on bedload transport.

The formation of these bedforms is still the object of discussion among scientists but very few experiments and data have been published. A laboratory experiment on cluster hydrodynamics was published by Brayshaw et al. (1983) while field studies were reported by Reid and Frostick (1984) and Brayshaw (1985). These authors assert the threshold of entrainment for clustered particles is higher than for the other loose grains and the bed may act as if it consisted of coarser material. As the cluster breaks down several particles are released and this may account for temporal and spatial variations of bedload transport rate.

The bedload yield of the Cyff and the Tanllwyth has an irregular pattern

(Newson, 1980) and it was supposed that cluster bedforms were one of the possible causes for that. Thus the number of pebble clusters occurring on the bed of the studied streams was surveyed aiming to evaluate the consistency of this hypothesis.

Transverse ribs have been observed in the field by several authors. Koster (1978) described their characteristics in detail and related them to the flow parameters suggesting transverse ribs are relict antidune bedforms. Very few laboratory studies have been reported on the formation of transverse ribs which, in the flume experiments, seem to form beneath an upstream-migrating hydraulic jump (McDonald and Day, 1978) or undular jump (Becchi and Marchi, 1973). No data has been published on the effect of transverse ribs on particle entrainment, but it is probably of the same order of magnitude as pebble clusters.

4.3.1 Pebble clusters

Pebble clusters were first recognized in the field by Dal Cin (1968), but scientists became more confident about them after the work of Brayshaw (Brayshaw et al., 1983; Brayshaw, 1984; Brayshaw, 1985). According to this author a pebble cluster consists of "the obstacle clast, the accumulation of particles on the obstacle's stoss side and the accretion of grains in the obstacle's downstream wake". This is the more general form of clusters, but a preliminary inspection of the bed of the Cyff and the Tanllwyth revealed that commonly one of the three components of a cluster may be lacking or show specific characteristics. A classification of cluster bedforms (Fig.3), based also on the author's observations on a few Italian gravel-bed streams (Billi, unpublished data), was then adopted.

According to this classification the Type A cluster corresponds to a complete cluster with its three components as described by Brayshaw (1984).

The Type B consists only of the obstacle and stoss particles while the wake grains are lacking.

The Type C cluster has instead no stoss particles and the obstacle and the wake grains only occur. Types B and C are then incomplete clusters.

In the Type D cluster none of the three components as defined above can be recognized. It consists in general of three or more particles packed in a well-imbricated position without a distinctive obstacle or a fine wake. Often, in these imbricated clusters, fine grains can be deposited between adjacent particles; rarely, the contacts between the larger imbricated particles may be locally performed through the finer grains (Fig.3). This poses some interesting questions, difficult to answer at present, about the formation of this type of cluster.

The Type E differs from Type A only in the size of the stoss particles which are anomalously larger than the obstacle.

When two Type A clusters lie closely on the stream bed with the wake of the upstream cluster ending by the stoss of the downstream one, a 'Periodic Cluster' (Fig.3) finally results.

The hydrodynamic behaviour of the different types of clusters is not known but their effects on particle entrainment and consequently on bedload transport can be very variable. For example, when the obstacle of a Type C cluster is removed only fine grains are released (since the stoss clasts are lacking), while the coarser

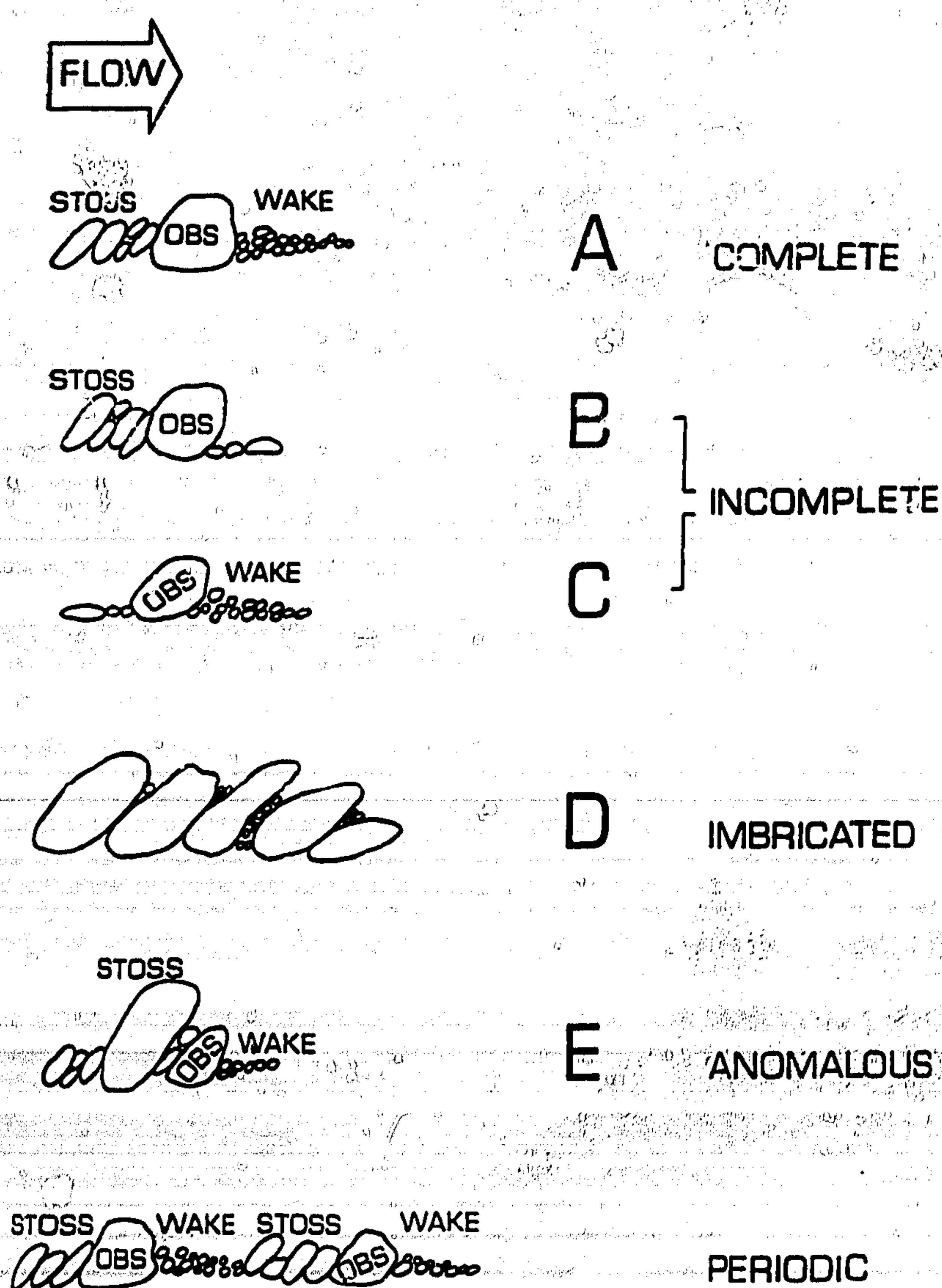


Fig.3 *Schematic classification of the different cluster types.*

stoss particles are instead entrained if the obstacle of a Type B moves.

The survey of the cluster bedforms was made by inspecting the bed of the studied streams and recording the number of each type of cluster occurring. The total number of clusters observed on the Cyff and the Tanllwyth was respectively 888 and 236 (the actual number of clusters of the Afon Cyff is very probably a little larger because their identification was not possible on a few sites whose bed was covered by a thick algal drape). The catchment of the Cyff is about four times larger than that of the Tanllwyth and the same ratio seems to exist between the cluster numbers.

On average one cluster every two metres of length occurs on the sediment reaches and the volume of bed material relative to the total number of clusters is lower than the variations in bedload yield observed for the Cyff but more for the Tanllwyth (Newson, 1980). Consequently it seems hard to postulate any large quantitative effect of pebble clusters on sediment transport.

Figure 4 shows the frequency distributions of the different cluster types for both streams. The clusters of the Cyff consist mostly of the Types A and C while in the Tanllwyth the modal classes are represented by the Types A and D. Imbricated clusters are more abundant on the Tanllwyth probably because it has a higher gradient and floods have a more flashy character with a steep falling limb and a consequent sudden deposition of bed material. To obtain more evidence of this it may be useful to analyse the cluster types distributions for different site morphologies (Fig.5).

On the Cyff, the frequency distributions of the cluster types is approximately the same for the pools, riffles, stepped pools and lateral bars. The modal classes are always represented by Types A and C while Type D is the less common cluster. For the Tanllwyth the distributions are instead more variable (Fig.5). In the pools the Type E clusters are the most common. This may be explained by the abrupt deposition of large particles which, as the flow wanes, are less easily transported on the pool bed and the impact with another particle, though smaller, may halt their movement. Such an explanation implies that particles of even very different size may have the same mobility. There is no field evidence of that for steep mountain streams whereas a few data have been reported for gravel-bed rivers (Andrews and Parker, 1985; Billi and Tacconi, 1985).

On the riffles of the Tanllwyth the most common cluster type [illegible] is Type D. As previously observed, imbricated clusters seem to be the most stable on a steep stream bed. The Cyff riffles have a low gradient and no particular increase in the Type D frequency results (Fig.5).

The cluster distribution of the stepped pools is almost identical to that of the whole stream (Fig.4). The lateral bars are instead characterized by an unusually high percentage of Type B clusters. Unfortunately very few data on the hydrodynamic behaviour of pebble clusters are available, but in this case it seems reasonable to consider Type B as relict Type A clusters whose wake grains have been washed away by transverse flow commonly occurring on lateral bars during declining flood flow. The average number of pebble clusters per site is reported in Table 4. These data show that clusters are less common in the pool sites of both the Cyff and the Tanllwyth. This result is consistent with the theory of bottom velocity/mean shear stress reversal as described by Keller (1971) and Lisle (1979). Pebble clusters can be considered as 'self-supporting bedforms' which develop with difficulty under high turbulence conditions like those occurring on a

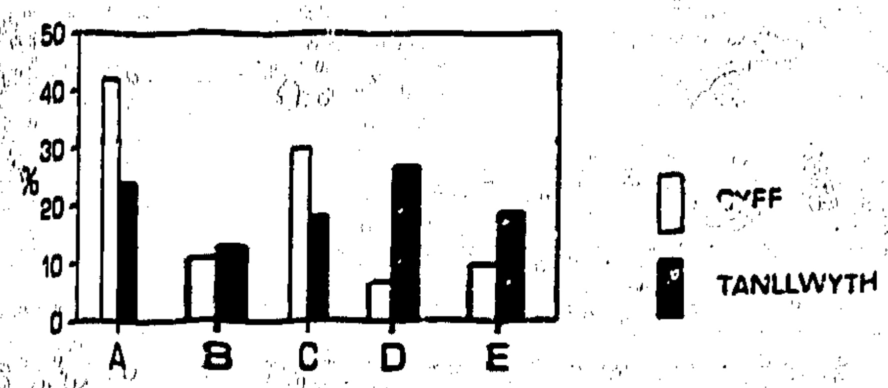


Fig.4 Frequencies of the different cluster types. The histograms are based on the cumulative data relative to the surveyed sediment reaches of both the studied streams.

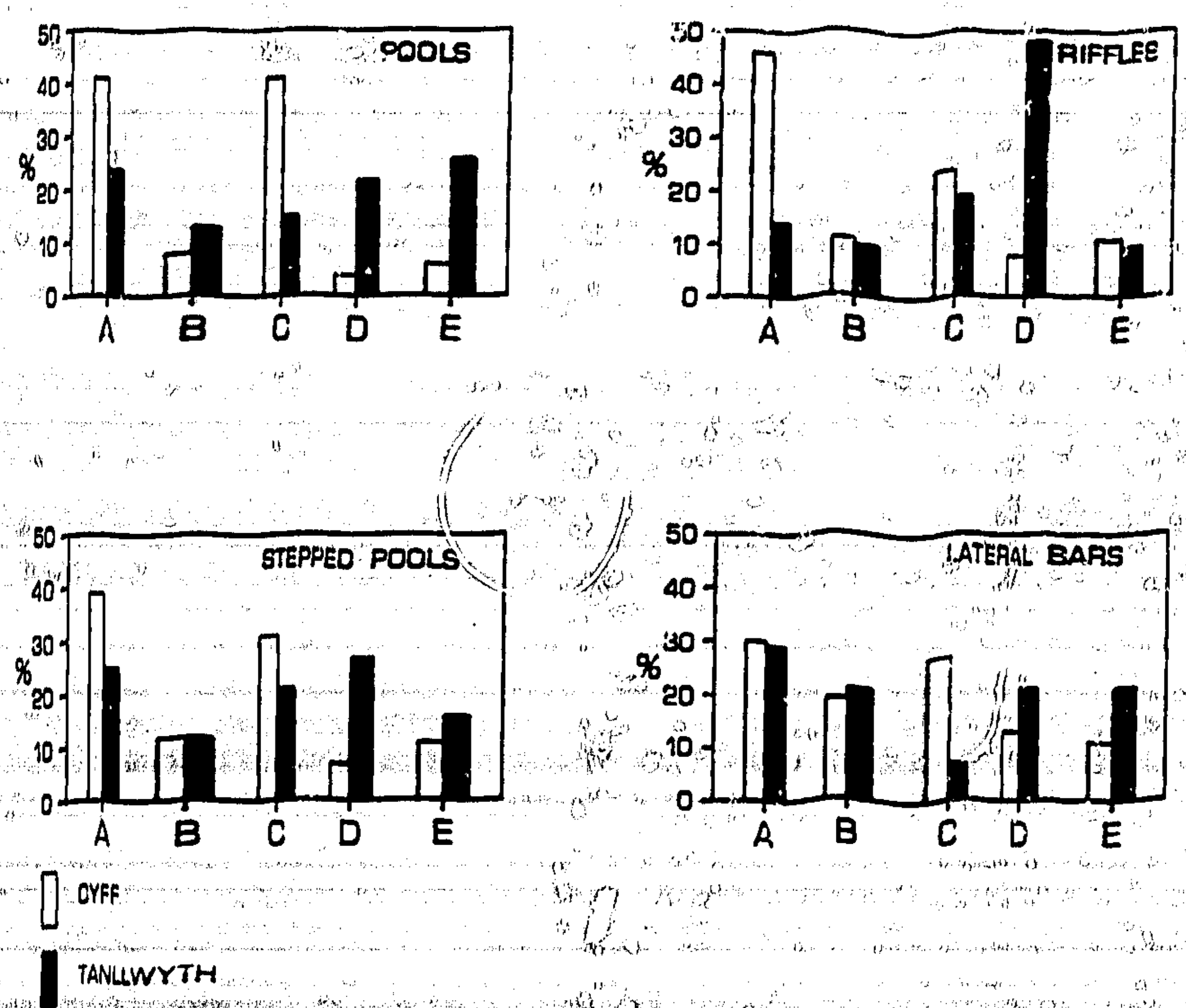


Fig.5 Frequency histograms of the different cluster types occurring on the bed of sites with different morphology.

pool bed during near bankfull discharge. On the other hand, on riffles turbulence is less at high discharges, and clusters can form more easily as shown by the large number of clusters per riffle site of the Cyff (Table 4). This conclusion seems not to be supported by the few clusters surveyed on the riffle sites of the Tanllwyth but here riffles are [illegible] developed as on the Cyff and their differentiation from stepped po[illegible]ly morphological than hydrodynamic.

Table 4

Average number of clusters per site

	Cyff	Tanllwyth
Pool	10	6
Riffle	22	6
Stepped pool	15	8
Lateral bar	13	14

On both the studied streams periodic clusters are so few that their influence on the variations of bedload transport rate observed by Newson (1980) can be disregarded.

The frequency distributions of the different cluster types were also reported reach by reach (see Appendix B) but no trend along both the water courses was discernible.

4.3.2 Transverse ribs

Transverse ribs are not a very common bedform on the studied streams. Their total number was 90 for the Cyff (for this figure does not refer to the whole stream as a few sites were covered by a thick algal drape and transverse ribs could not be surveyed) and 30 for the Tanllwyth. The distribution of transverse ribs per site with different morphology is reported on Table 5.

Table 5

Average number of clusters per site

	Cyff	Tanllwyth
Pool	0.2	1.0
Riffle	4.2	2.3
Stepped pool	0.4	0.4
[illegible] bar	1.8	0.0

The data of Table 5 show that transverse ribs form mostly on riffles. Here, either antidune or hydraulic jump commonly occur, even jointly, thus both the conditions considered as necessary for their formation are satisfied. However, nothing supports one of the above mentioned hypotheses about how transverse ribs are generated.

4.4 Size and shape characteristics of the bed particles

Many studies have been published on the grain-size and shape characteristics of the bed sediment and their variations along alluvial channels. Much less is known about such features and their variations on steep mountain streams strongly controlled by bedrock.

The Cyff and the Tanllwyth consist of alternate bedrock and sediment reaches of variable length which give rise to a particular system in which the sediment characteristics reflect physical conditions different from those occurring on purely alluvial channels. In order to verify this hypothesis several samples of bed material were taken and analysed.

4.4.1 Sampling procedure

Sediment samples were taken from the bed surface of the sediment reaches 1 to 5 of the Cyff and 1 to 6 of the Tanllwyth (Fig. 2).

The procedure adopted was the transect sampling. Transverse lines, spaced 5 to 10 m depending on the reach length, were set across the thalweg and a pebble every 20 cm was taken from the bed surface. On average, every transect section gave about 20 particles.

The longest, intermediate and shortest axis of each particle were measured with a caliper in order to get as precise as possible values of mean diameter, sphericity, flatness and shape.

Such data obviously refers to the armoured layer and certain discrepancies with the size and shape characteristics of the sediment captured by the bedload traps on the Cyff and the Tanllwyth (Institute of Hydrology, unpublished data) may be expected. A comparison between the armour and bedload characteristics could be very helpful in our understanding of the sediment transport processes.

4.4.2 Grain-size distribution

The mean diameter of each particle was measured by averaging the three mutually perpendicular 'a', 'b' and 'c' axes (long, intermediate and short, respectively). The obtained values were then grouped into fixed classes arranged on a 1/2 phi scale and reported as percentage by number on probabilistic diagrams.

Figure 6 shows the grain-size distributions regarding all the surveyed reaches of the Cyff and the Tanllwyth. The two curves are very similar although only the downstream reaches of the Cyff (which is longer than the Tanllwyth) were investigated. This result may have two main explanations. The sediment supplied to the Cyff is probably coarser than that of the Tanllwyth and this fact is consistent with a wider occurrence of Pleistocene glacial and periglacial deposits in the catchment of the Cyff. Secondly, both streams are characterized by a particular morphology consisting of bedrock reaches separating sediment reaches in which the sediment size and sorting seem to depend on local factors. In fact,

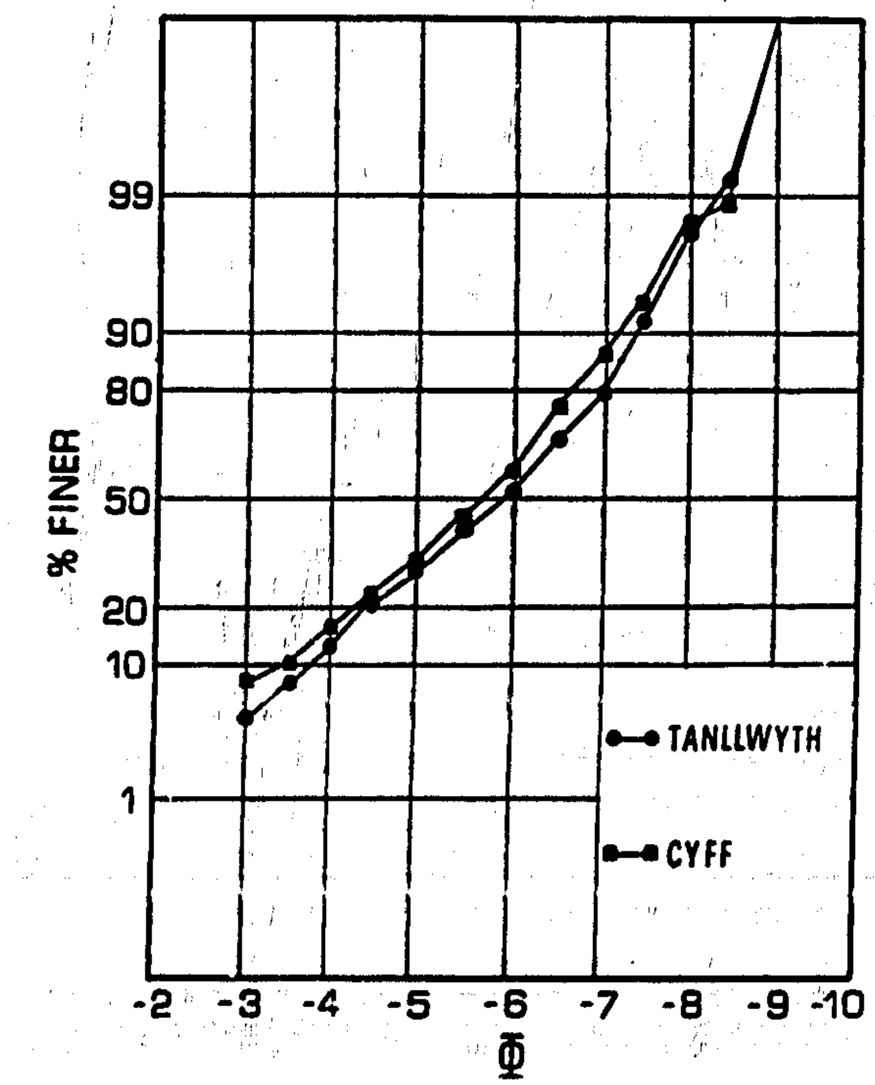


Fig.6 *Grain-size distributions based on all the bed sediment data gathered for the studied streams.*

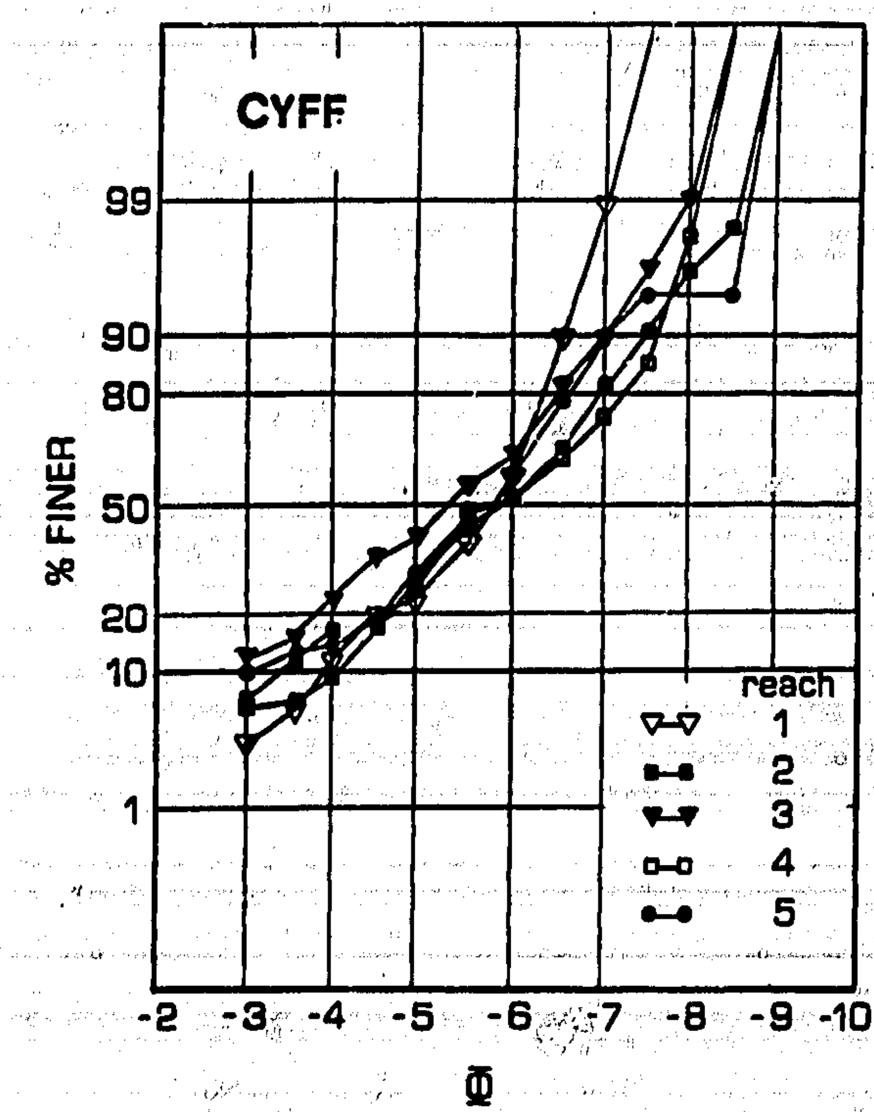


Fig.7 *Grain-size distributions: the bed material of the surveyed sediment reaches of the Cyff.*

the grain-size distributions of the bed material reported for each single sediment reach on Figures 7 and 8 (see also Appendix C) show no downstream decrease in particle size. In the Tanllwyth, for example, the bed sediment of the most upstream reach 6 is finer than that of the downstream reach 2 but rather similar to that of the utmost downstream reach 1.

These data suggest that each sediment reach reacts to external factors as a single unit. Such factors can be very important within a reach but their effects seem to be largely diminished and rarely transmitted beyond the bedrock outcrops into another sediment reach. Furthermore, the bedrock reaches themselves can be an important source for bed material and coarse particles may be delivered into the downstream sediment reaches.

The bedload captured by the traps on the Cyff and the Tanllwyth is far finer than the surface material actually surveyed (Newson, 1982, unpublished data) but the bedload median sizes of the two streams are similar and compare well as do the grain-size distributions of the armoured layers.

This conclusion poses the interesting question whether similarities or differences in the grain-size distributions of the armoured layers of different streams are repeated in space and time and what is their relation to the material that moves as bedload. Further investigation is needed to answer this question and other data coming from streams with different characteristics should be compared with those of the Cyff and the Tanllwyth.

The standard deviation, skewness and kurtosis were also calculated for each frequency curve with the method of moments. These three parameters are quite constant along the two water courses and no trend seems to exist (see Appendix C) as well as seen for the mean size.

4.4.3 Roundness

The particle roundness was measured using the method suggested by Dobkins and Folk (1970). According to these authors roundness can be expressed as the ratio between the diameter of curvature of the sharpest corner and the diameter of the largest inscribed circle of a particle lying on its maximum projection plane.

The frequency distribution of roundness for the bed pebbles of the Cyff and the Tanllwyth is shown on Figure 9. The two curves are almost identical and show that the bed material of the studied streams is rather poorly rounded with a mean value around 0.3. This result is consistent with the length and the mountain physiography of both streams but more rounded clasts would be expected on the Cyff since it is longer than the Tanllwyth and since only its downstream reaches were sampled. Nevertheless the rounding processes seem to be active along the Cyff, Tanllwyth, whose bed sediments are of comparable resistence to abrasion, and a small downstream increase in roundness occurs (Figures 10 and 11). This indicates that the difference in stream length is not enough to differentiate the studied streams in terms of particle roundness.

The large bedrock reaches probably play an important role in maintaining the low average pebble roundness. They are commonly very steep and characterized by a tumbling flow and small cascades so that pebble breaking occurs even in the downstream reaches.

Another interesting point came out while measuring the roundness parameters of so many particles. During such measurement it was clearly evident, just handling the pebbles, that almost all the bed samples consisted of two definite populations: a very angular one and another well rounded one. A bimodal distribution would therefore be expected on Figure 9. The two curves of Figure 9 are however quite close to a normal distribution. The Dobkins and Folk method (1970) is certainly one of the most precise, but its accuracy seems to decrease when large differences in grain size occur. The operator is in fact subjected to much more hesitation when looking for the sharpest corner of large boulders where very small irregularities of their silhouette can be more easily seen and measured. The result is that the larger the diameter of the largest inscribed circle the smaller may be the diameter of curvature of the sharpest corner. It introduces an error which at present has not been determined. This problem needs a review of the available methods and further investigation.

4.4.4 Sphericity

The Folk's index (1958) was used to indicate the particle sphericity. The frequency distribution curves relative to the Cyff and the Tanllwyth are again very similar, as shown by Figure 12. Only a slight difference occurs as a relatively higher percentage of very spherical pebbles for the Cyff. However, both curves are quite close to a normal distribution with a mean value around 0.5 (i.e. half way to a perfect sphere).

The studied streams are rather short and the sorting processes are scarcely effective (see the previous chapters): the sphericity of their bed particles is then largely influenced by the sphericity of the parent material on the slopes. The observation of Figure 13 and 14 leads to the same conclusion. There is in fact no trend of downstream increase in sphericity as would be expected.

4.4.5 Flatness

The particle flatness was measured by the Cailleux's index (1945). The diagrams of Figure 15 report the flatness frequency distributions for the bed particles of the Cyff and the Tanllwyth. The curves are rather similar as are the distributions relative to the surveyed sediment reaches (Fig. 16 and 17). Flatness is a morphometric particle property which is substantially the opposite of sphericity. Consequently the information on the sediment dynamics in a steep mountain stream which can be obtained from this parameter is comparable with that resulting from the analysis of particle sphericity. The mean flatness of the bed material of the Cyff and the Tanllwyth is around 3.5. A discoidal pebbel with such a Cailleux's flatness index has also a Folk's sphericity index of about 0.5. It corresponds to the average sphericity found for the studied streams.

4.4.6 Oblate-Prolate

The oblate-prolate index (Dobkins & Folk, 1970) is a measure of particle shape more accurate than sphericity. In fact, a thick disc and a thin rod may have the same numerical sphericity value, but they are absolutely different in shape. Shape is an important factor influencing the entrainment and, once in motion, the travelling distance of a particle.

The form of a pebble may depend on many factors. The most important of them is the original shape of the clasts as yielded by bedrock jointing and weathering processes. The catchments of the Cyff and the Tanllwyth are

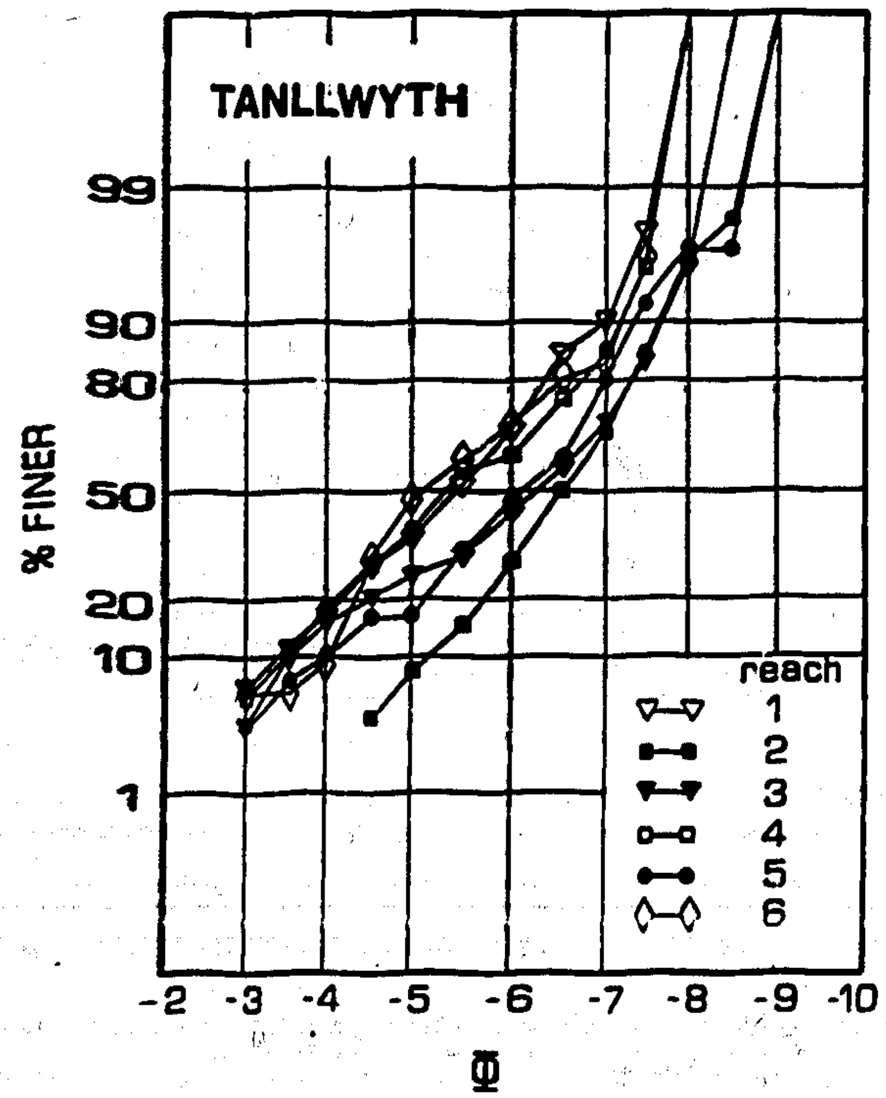


Fig.8 *Grain-size distributions: the bed material of the surveyed sediment reaches of the Tanllwyth.*

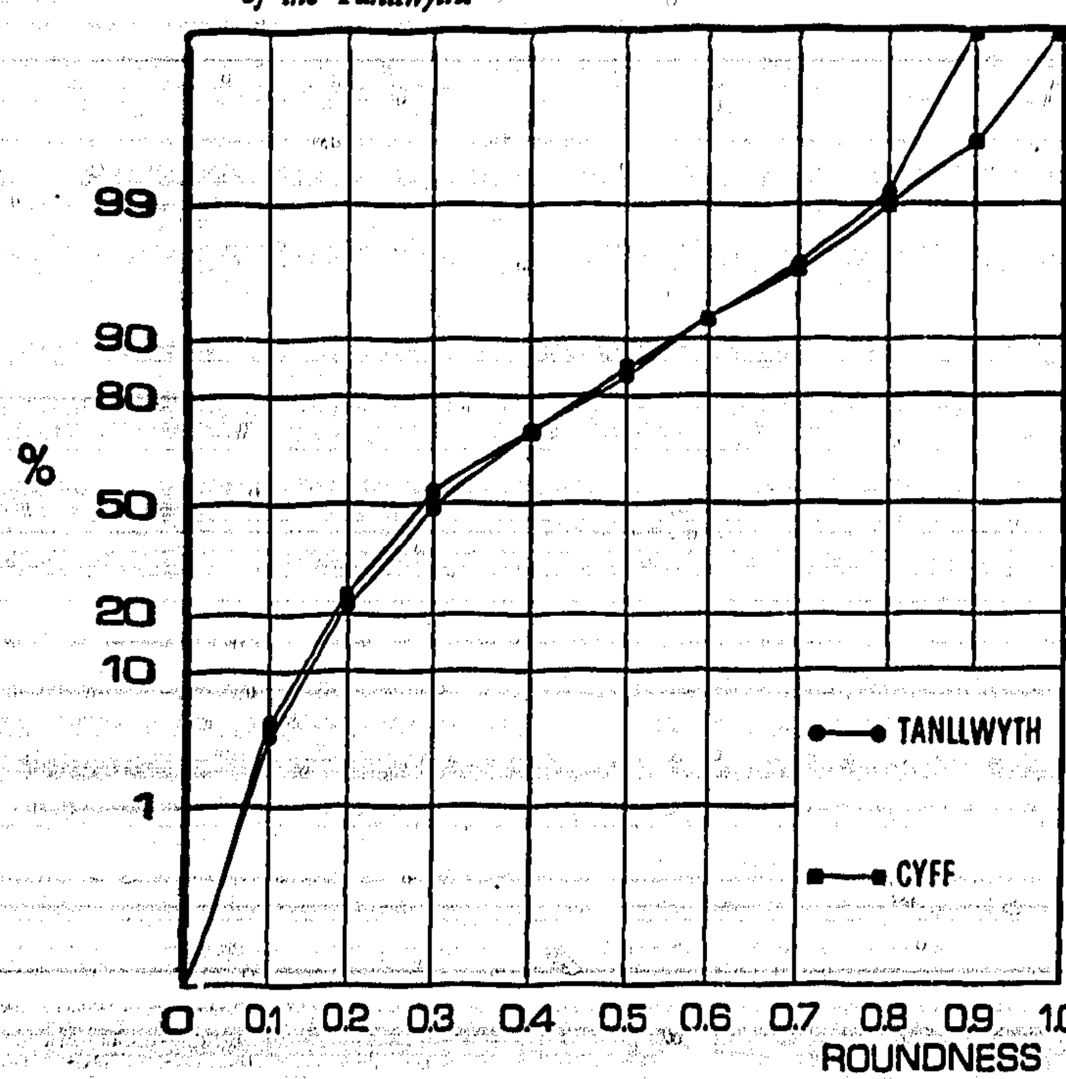


Fig.9 *Particle roundness frequency curves based on all the data gathered on the bed of the studied streams.*

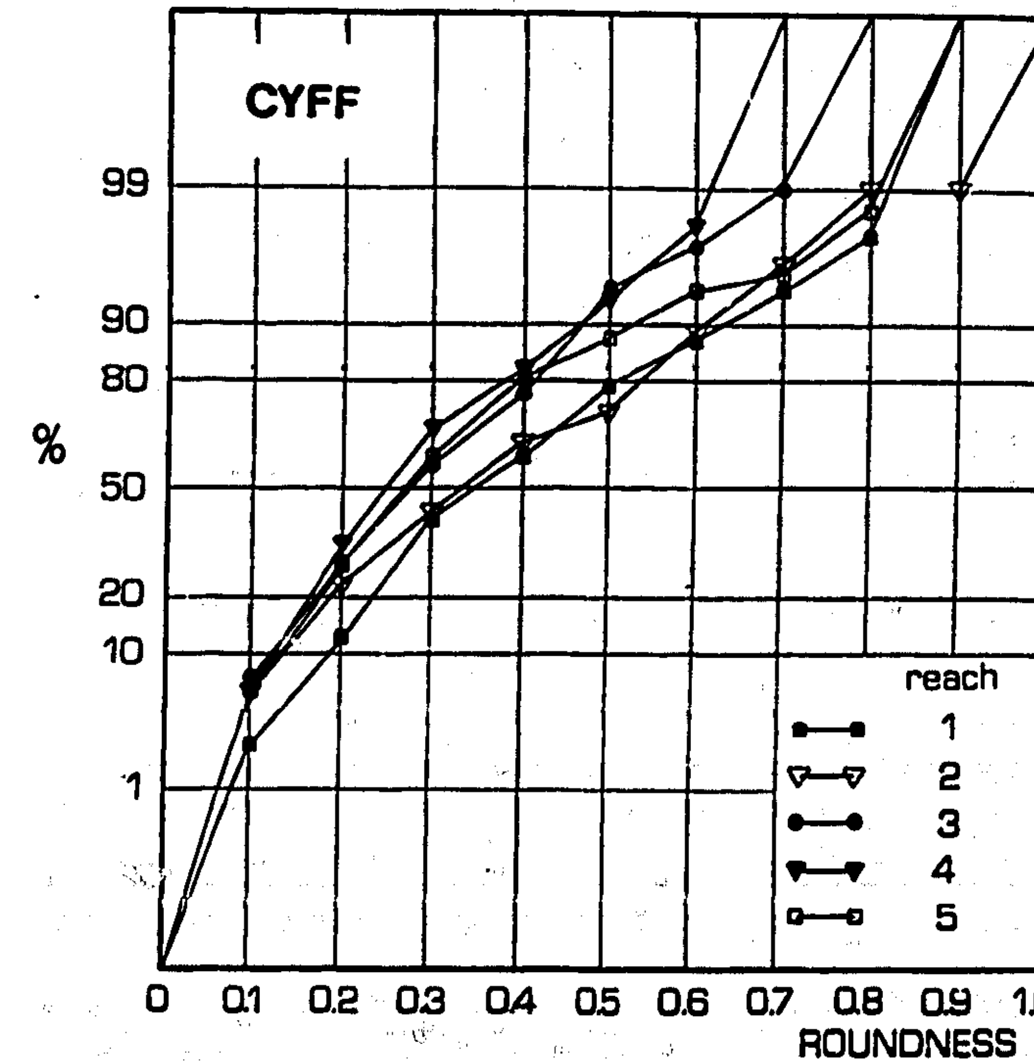


Fig.10 *Roundness frequency curves: the bed particles of the surveyed sediment reaches of the Cyff.*

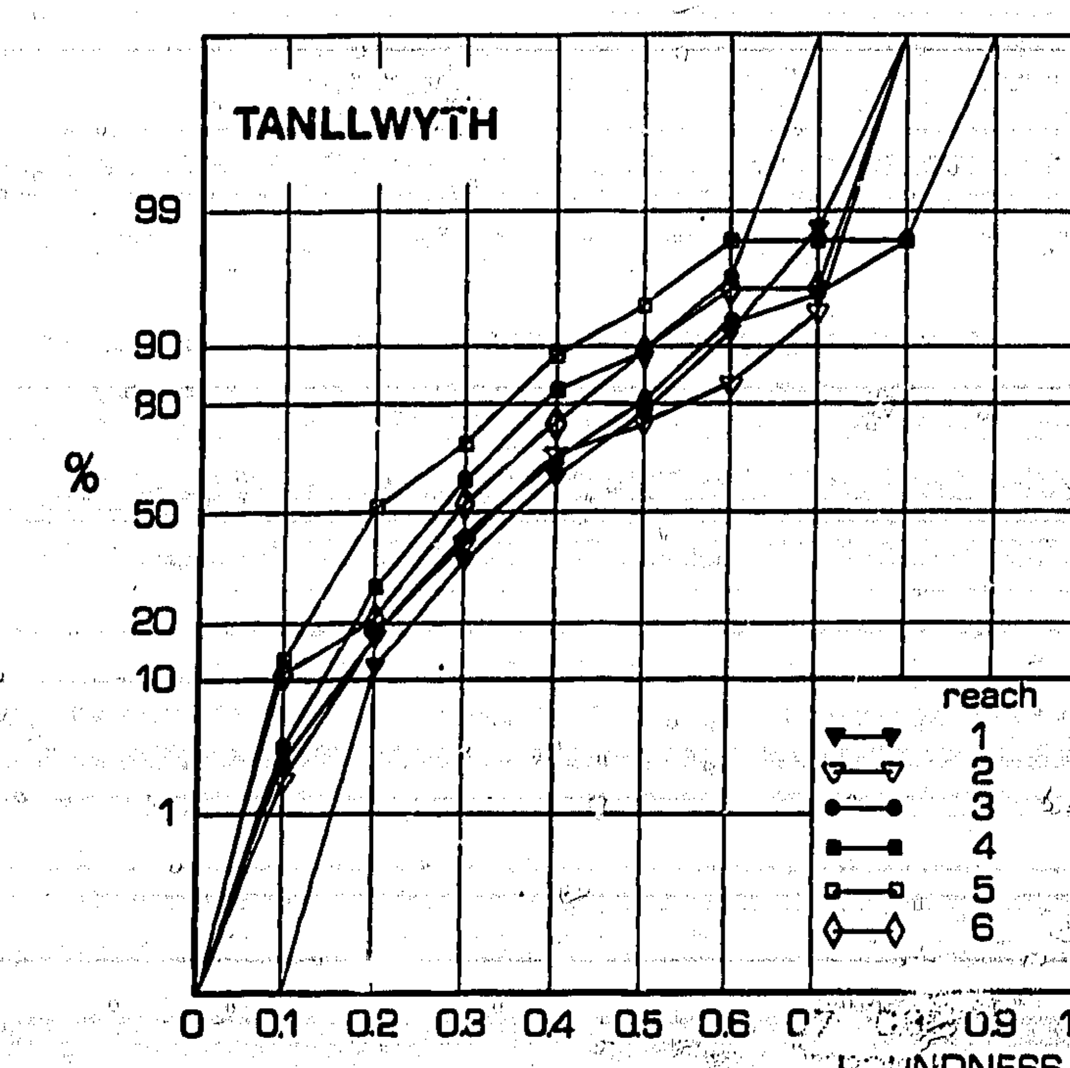


Fig.11 *Roundness frequency curves relative to the bed particles of the surveyed sediment reaches of the Tanllwyth.*

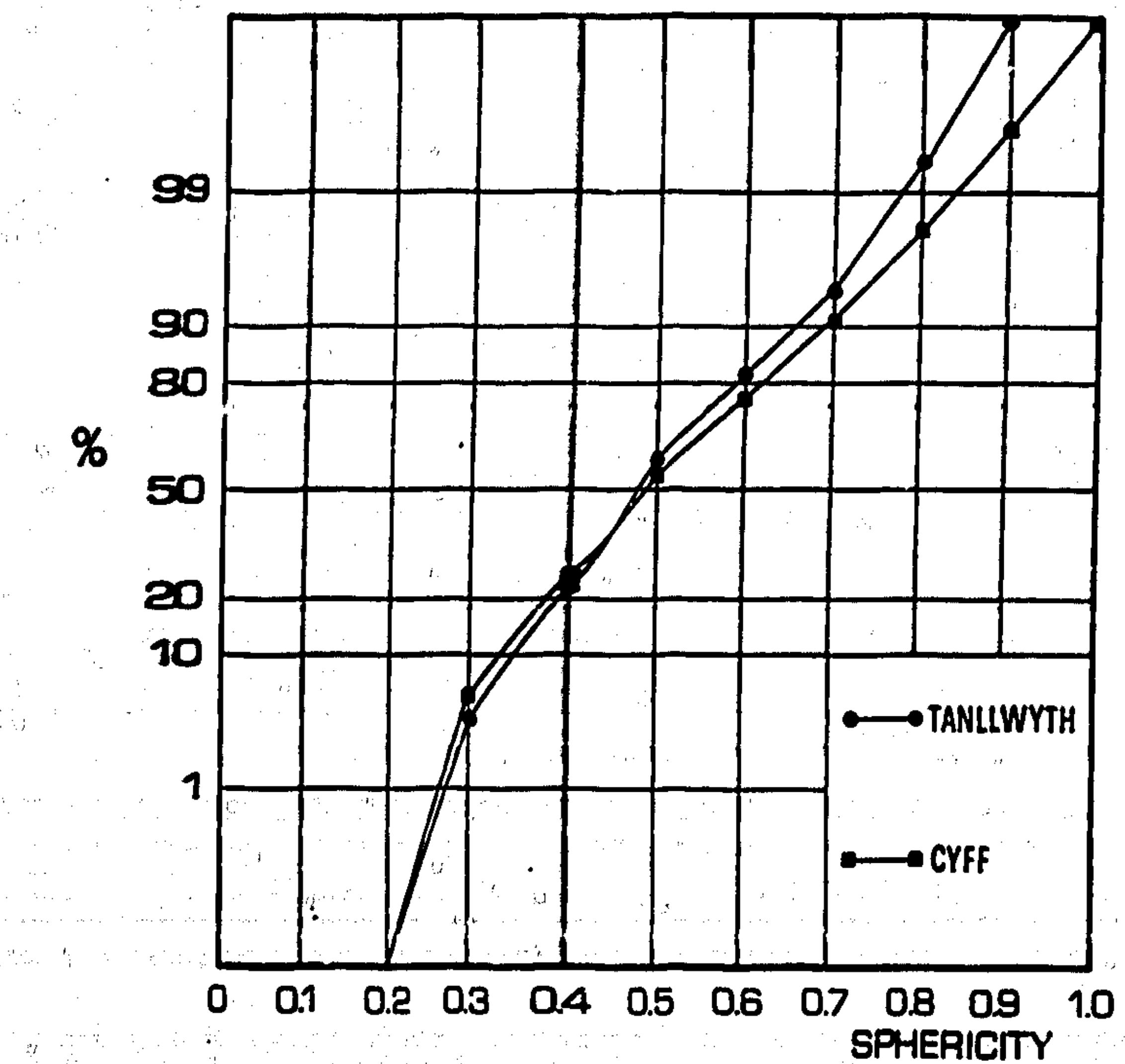


Fig. 12 *Particle sphericity frequency curves based on all the data gathered on the on the bed of the studied streams.*

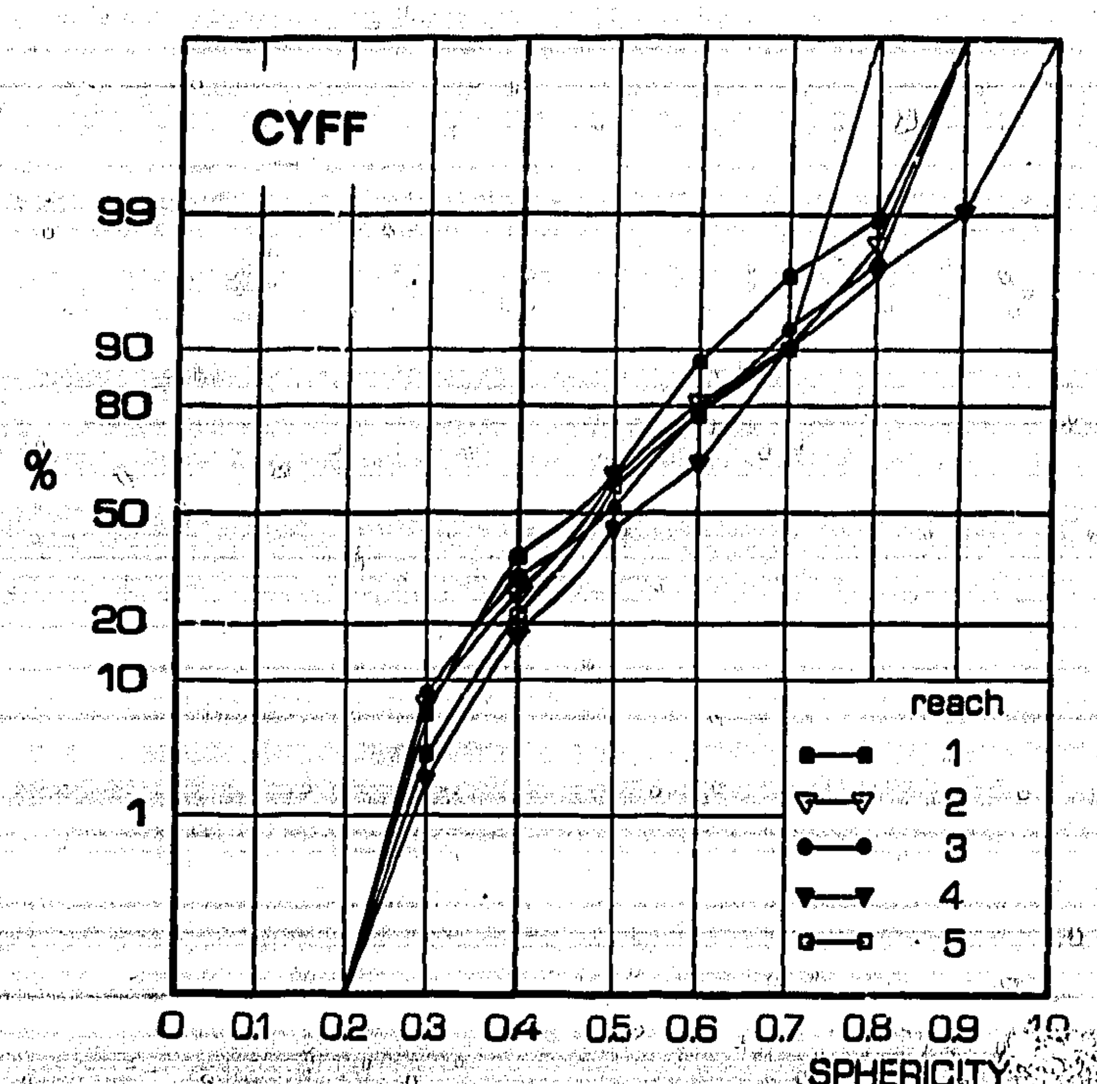


Fig. 13 *Sphericity frequency curves: the bed particles of the surveyed sediment reaches of the Cyff.*

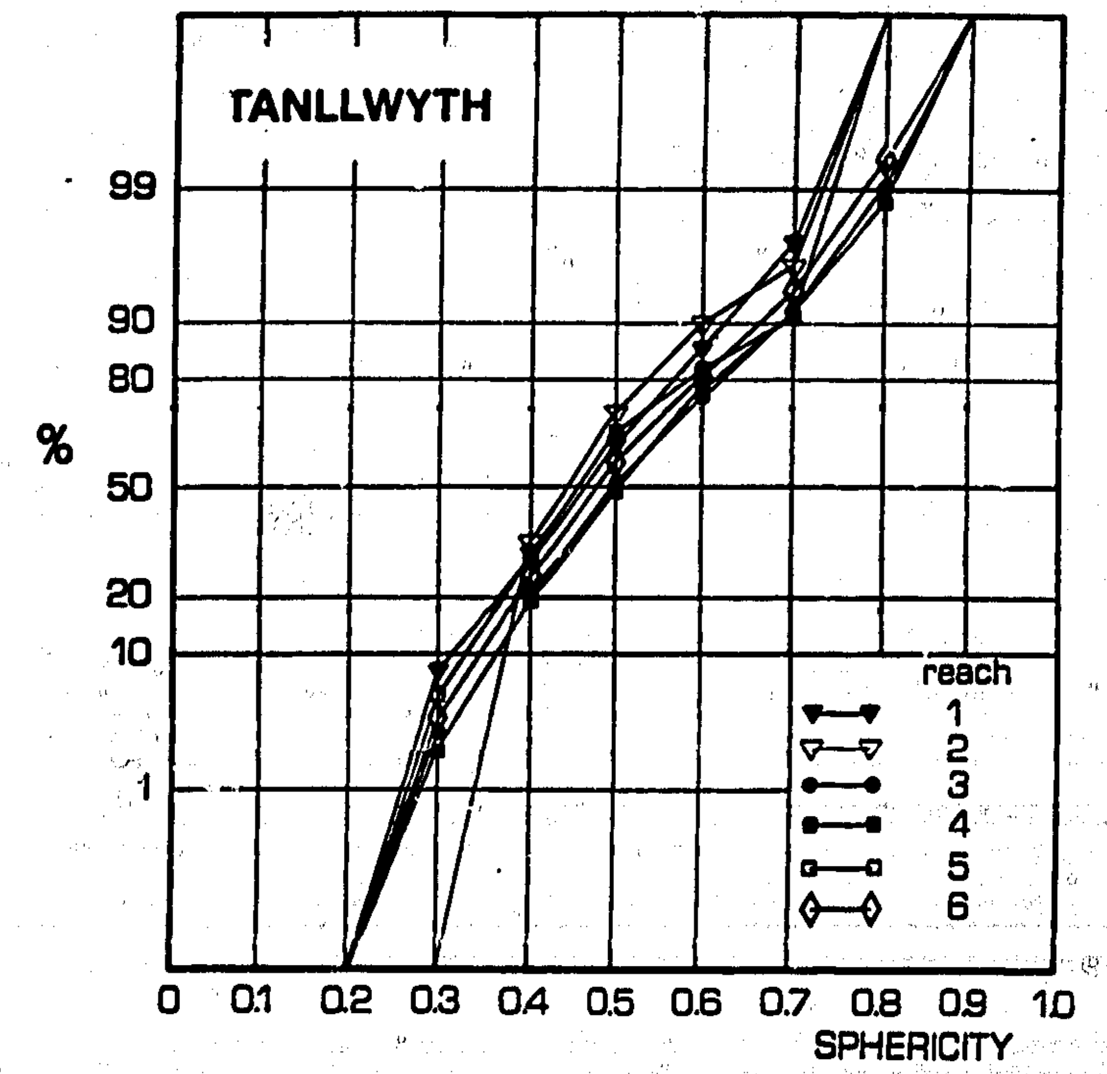


Fig. 14 *Sphericity frequency curves: the bed particles of the surveyed reaches of the Tanllwyth.*

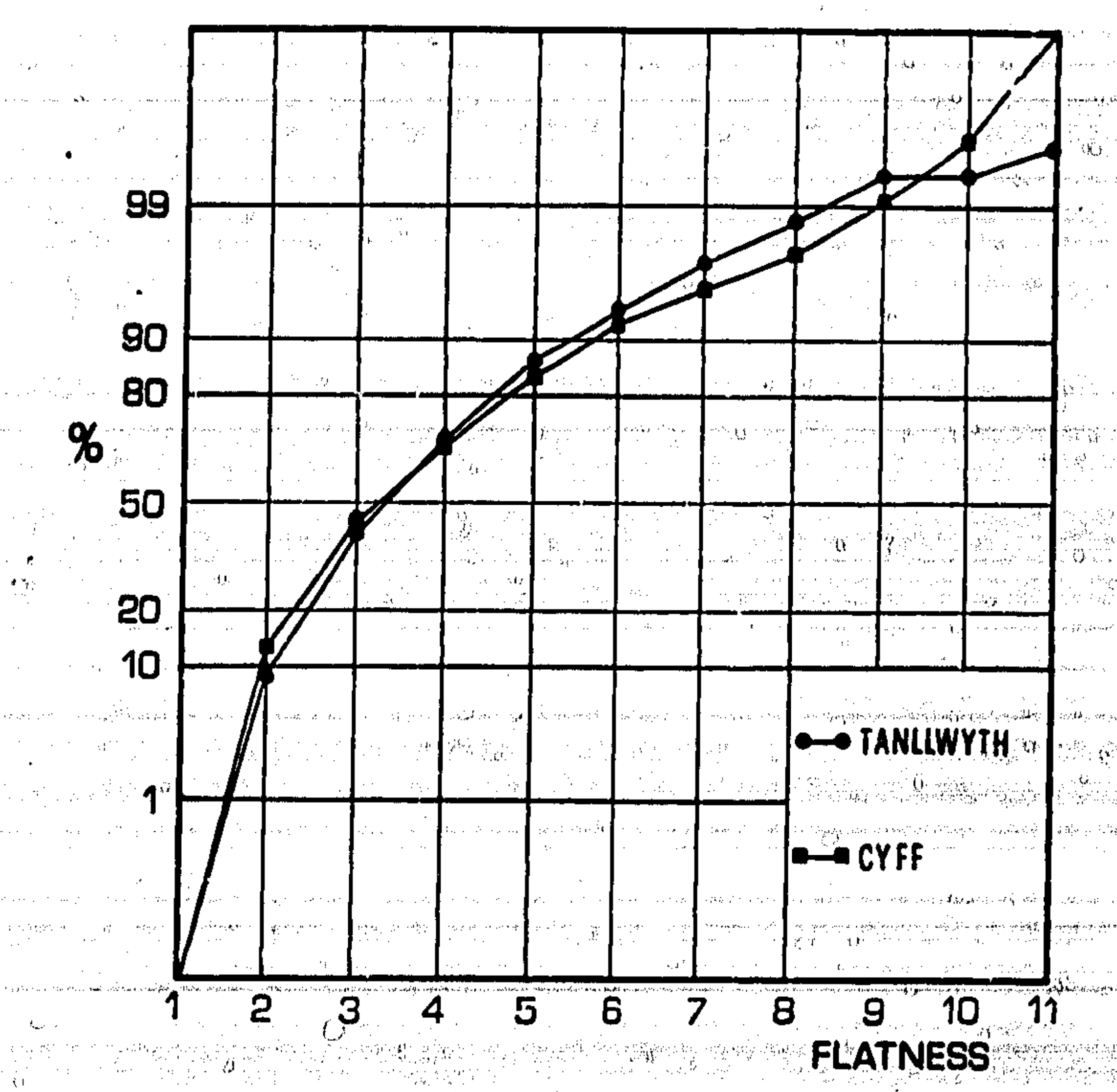


Fig. 15 *Particle flatness frequency curves based on all the data gathered on the bed of the studied streams.*

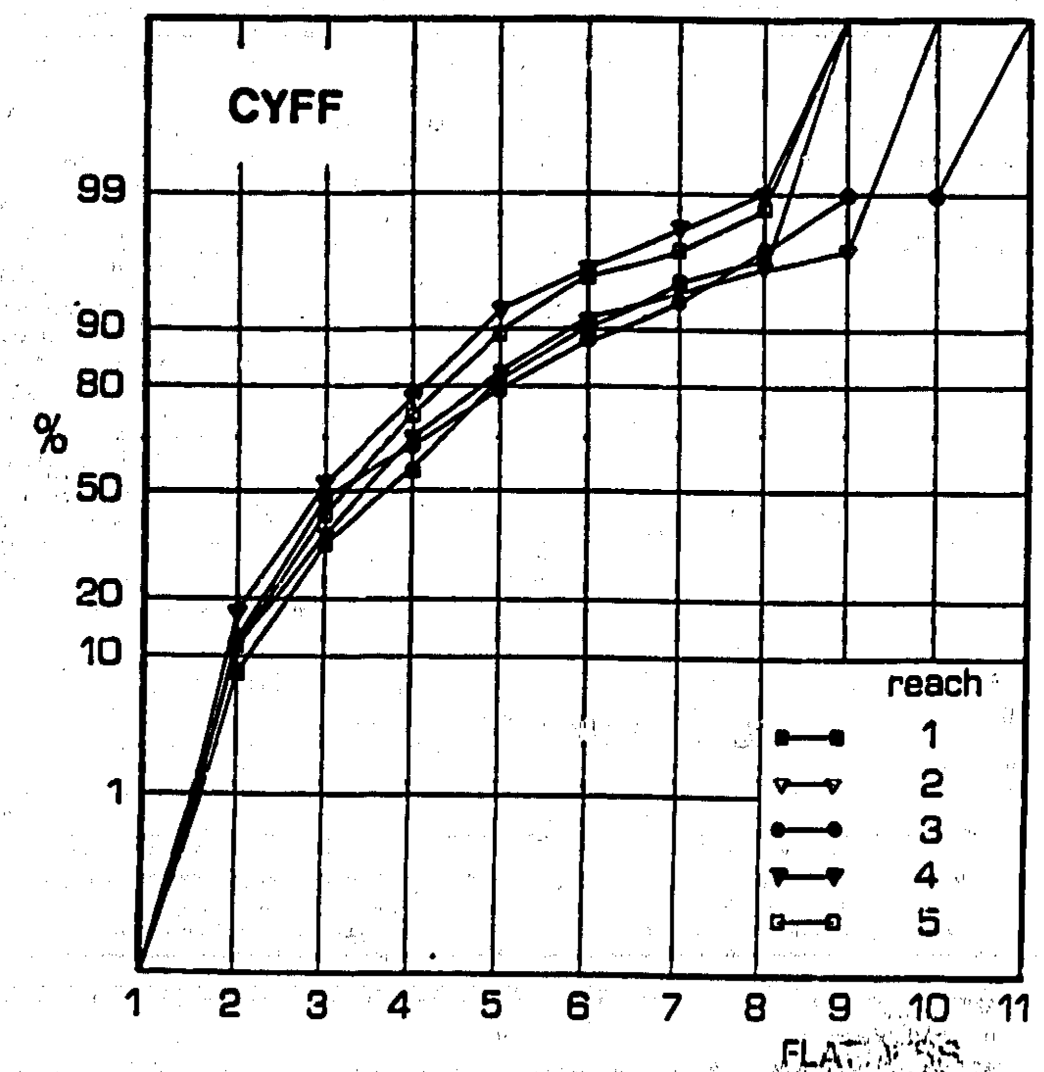


Fig.16 *Flatness frequency curves: the bed particles of the surveyed sediment reaches of the Cyff.*

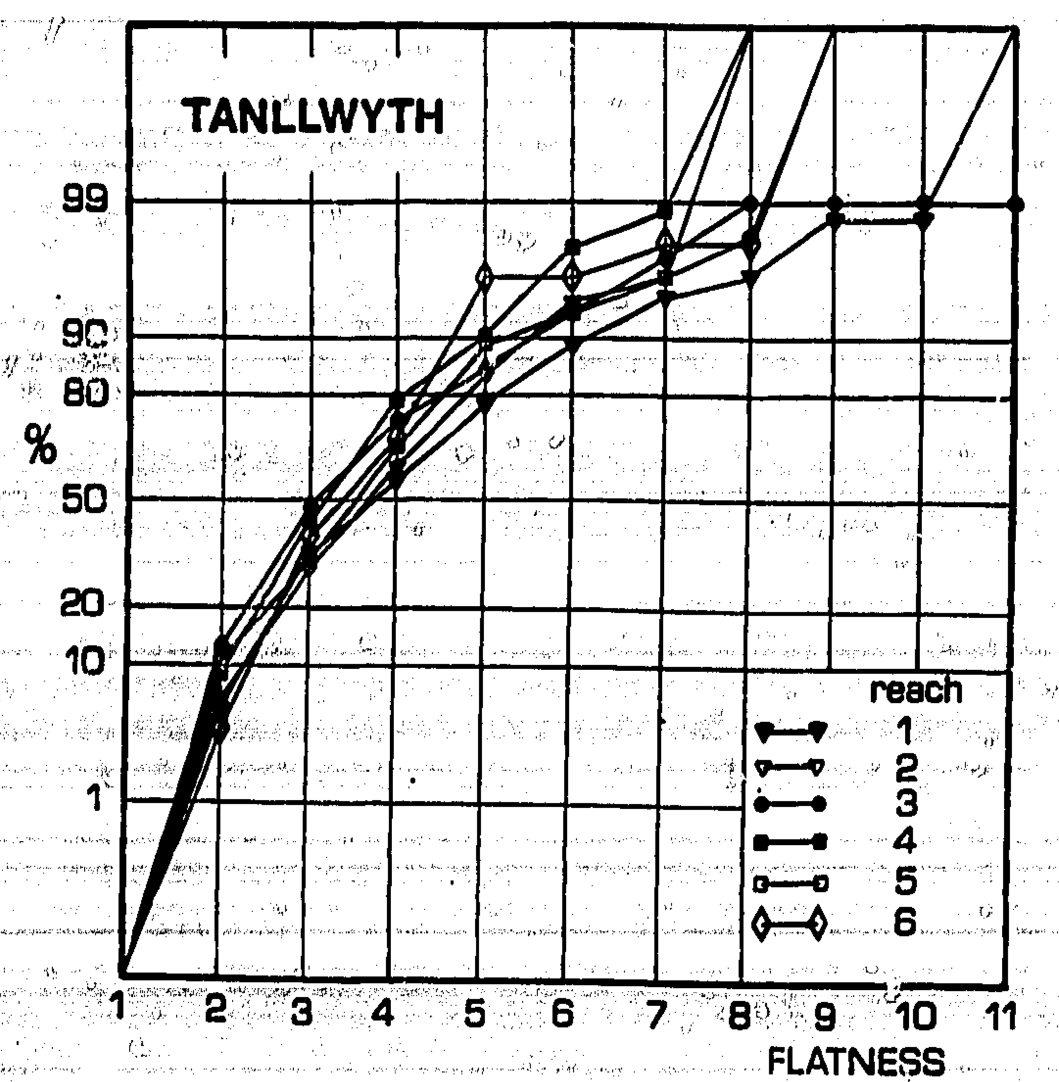


Fig.17 *Flatness frequency curves: the bed particles of the surveyed sediment reaches of the Tanllwyth.*

underlain by similar rock formations, consisting mainly of Silurian shales and mudstones (Newson, 1976, Appendix A), and consequently the shape of the bed particles of both streams is very similarly distributed (Fig.18). Equant pebbles are quite scarce (about only 15%) while the remaining 85% consists of almost equal proportion of discs and rodlike particles. Such a distribution reflects the short distance travelled by the sediment from the source areas to the stream bed. Moreover, about one third of the measured pebbles has an O-P index more than 10 or less than - 10 corresponding to an extremly elongated or thin discoidal shape. In a high energy environment like a steep mountain stream such particles are the less stable and their breakage can commonly occur, producing in general more equant smaller particles. The abundance of very prolate and very oblate particles seems then to support the hypothesis that they represent fresh-formed material coming in a large proportion from the catchment slopes.

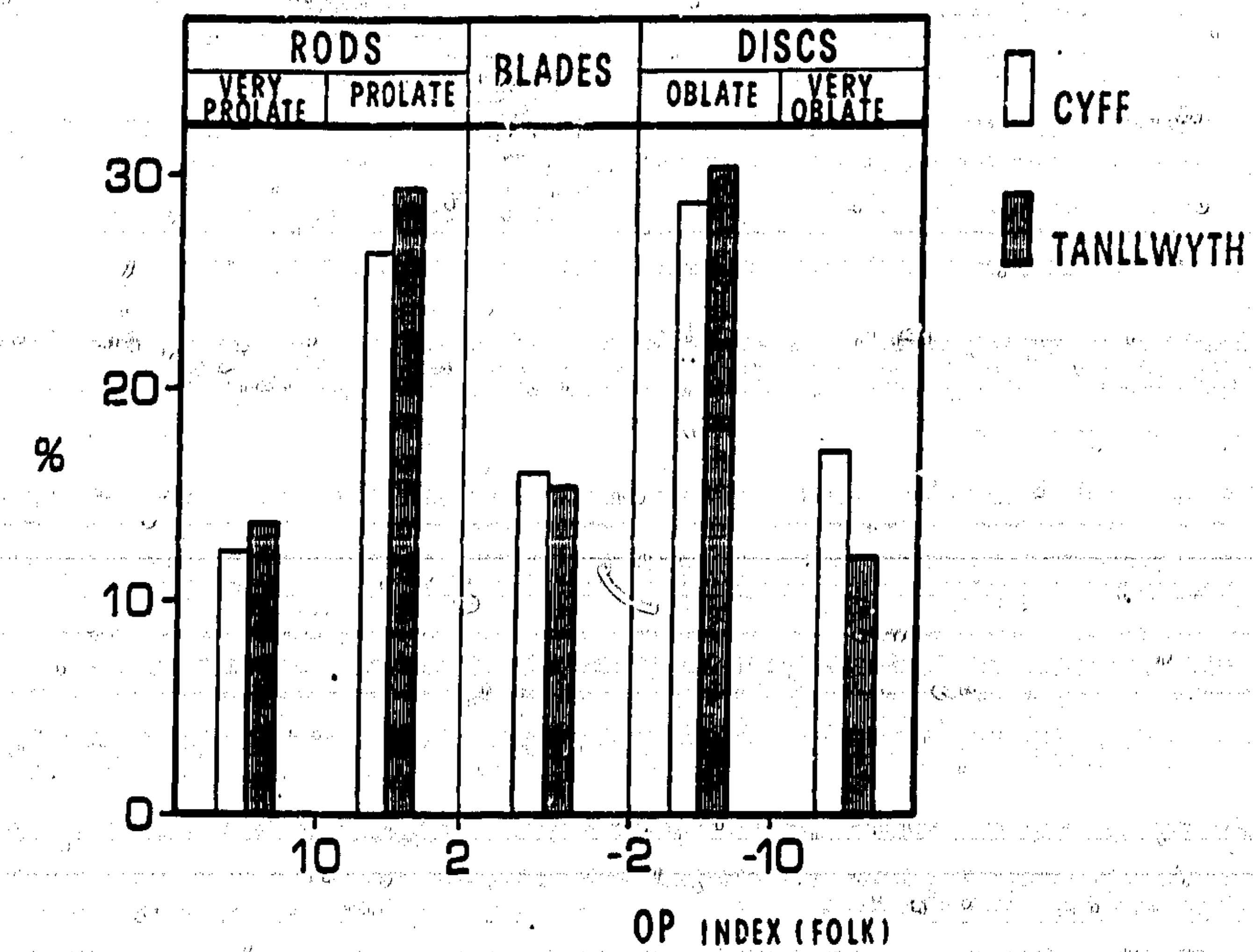


Fig.18 *Bar diagram showing the shape frequencies of the bed particles of the studied streams.*

Concluding remarks

Steep mountain streams have specific features different from purely alluvial channels. Bedrock control is an important factor acting on the morphology, the sediment transport and the sediment characteristics of streams like the Afon Cyff and the Nant Tanllwyth. Such streams are very small if compared with rivers like the Wye or the Severn, but they are environmentally very important because it is at their scale that most of the physical processes of upland denudation are performed.

The Cyff and the Tanllwyth showed a wide range of bedload yield, though with comparable discharges. Such variations seem to depend on the variable conditions of channel sediment storage and release more than on the effect of bedforms like pebble clusters on particle entrainment.

The grain-size distributions of the armoured layer of both streams are very similar as are the frequency distribution curves of the particle shape parameters (namely roundness, sphericity, flatness, oblate-prolate).

The studied streams are rather small and so close to the sediment source areas that the size and shape evolution of the bed sediment is not enough to differentiate them although the Cyff has a larger catchment than the Tanllwyth and a very different vegetation cover. Besides, the control exerted by the bedrock is possibly so strong as to affect the characteristics of the two streams at a higher degree than the other factors.

Acknowledgments

The author is greatly indebted to M.D. Newson whose critical review has largely improved this paper. I. Becchi is greatly acknowledged for the stimulating discussions and comments during the preparation of the first draft.

References

Andrews, E.D., Parker, G., 1985. The coarse surface layer as a response to gravel mobility. International Workshop on Problems of Sediment Transport in Gravel-Bed Rivers, Pingree Park, Colorado.

Becchi, I., Marchi, E., 1973. Bed-load influence on the undular jump. IAHR, XV Congr., Istanbul.

Billi, P., Tacconi, P., 1985. Bedload transport processes monitored at Virginio Creek measuring station, Italy. In Richards K.S. (ed): River Channel Dynamics, in press.

Brayshaw, A.C., 1984. Characteristics and origin of cluster bedforms in coarse-grained alluvial channels. In Koster, E.H. and Steel, R.J. (eds): Sedimentology of Gravels and Conglomerates. Canadian Soc. Petrol. Geol., Memoir 10, 77-65.

Brayshaw, A.C., 1985. Bed microtopography and entrainment thresholds in gravel-bed rivers. Geol.Soc.Am.Bull., v.96, 218-223.

Brayshaw, A.C., Frostick, L.E., Reid, I., 1983. The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels. Sedimentology, v.30, 137-143.

Cailleux, A., 1945. Distinction des galets marins et fluviatiles. Soc.Geol.France Bull., 5th serie, t.15, 375-404.

Dobkins, J.E. Folk, R.L., 1970. Shape development on Tahiti-Nui. Jour.Sed.Petrol., v.40, 1167-1203.

Keller, E.A., 1971. Areal sorting of bed-load material: the hypothesis of velocity reversal. Geol.Soc.Am.Bull., v.82, 753-756.

Koster, E.H., 1978. Transverse ribs: their characteristics, origin and paleohydraulic significance. In: Miall, A.D. (ed.), Fluvial sedimentology. Canadian Soc. of Petrol.Geol., Memoir 5, 161-186.

Langbein, W.B., Leop[illegible], L.B., 1968. River channel bars a[illegible]es - Theory of kinematic waves. U.S. Geol.Surv.Prof. Paper 422-L.

Laronne, J.B., Carson, M.A., 1976. Interrelationships between bed morphology and bed material transport for a small gravel-bed channel. Sedimentology, v.23, 67-85.

Lisle, T., 1979. A sorting mechanism for a riffle-pool sequence. Geol.Soc.Am.Bull., Part I, v.90, 616-617.

McDonald, B.C., Day, T.J., 1978. An experimental flume study on the formation of transverse ribs. Geol.Surv.Can., Paper [illegible]-1A, 421-451.

Newson, M.D., 1976. The physiography, deposits and vegetation of the Plynlimon catchments. Institute of Hydrology, Report 30, 60 pp.

Newson, M.D., 1980. The geomorphological effectiveness of floods - A contribution stimulated by two recent events in Mid-Wales. Earth Surface Processes, v.5, 1-16.

Newson, M.D., Harrison, J.G., 1978. Channel studies in the Plynlimon experimental catchments. Institute of Hydrology, Report 47, 61 pp.

Newson, A.J., 1976. Some aspects of the rainfall of Plynlimon, Mid-Wales. Institute of Hydrology, Report 34, 36 pp.

Reid, I., Frostick, L.E., 1984. Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channel. In: Koster, E.H., Steel, R.J., Sedimentology of Gravels and Conglomerates, Canadian Soc. of Petrol. Geol., Memoir 10, 61-68.

Reid, I., Frostick, L.E., Laymen, J.T., 1985. The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. Earth Surface Processes, v. 10, 33-44.

Sneed, E.D., Folk, R.L., 1958. Pebbles in the lower Colorado River. A study in particle morphogenesis. Journ. Geology, v. 66., 114-150.

Wittaker, J.G., Davies, T.R.H., 1982. Erosion and sediment transport processes in step-pool torrents. IAHS Publ. No.173, 99-104.

Appendix A

Site morphology distribution per reach (R)

CYFF

	R1	R2	R3	R4	R5	R6	R7	R8
Riffles	2	2	2	1	0	6	3	1
Pools	4	2	2	3	1	4	2	1
Stepped pools	1	2	0	2	1	8	1	2
Lateral bars	0	0	0	0	1	4	0	0

TANLLWYTH

	R1	R2	R3	R4	R5	R6	R7
Riffles	1	0	0	2	0	0	0
Pools	4	1	6	3	0	1	0
Stepped pools	1	3	2	6	2	2	1
Lateral bars	0	0	1	0	0	0	0

Average number of boulder steps in a stepped pool

CYFF	TANLLWYTH
5.5	3.5

Average channel width (W) and depth (D) (in meters) at bankfull discharge

CYFF

Reach 1		Reach 2		Reach 3	
W	D	W	D	W	D
2.80	0.67	3.80	0.61	5.00	0.56
2.80	0.66	4.00	0.52	5.00	0.46
4.60	0.53	5.00	0.49	7.00	1.00*
3.00	0.74	4.60	0.53	6.00	1.00*
2.60	1.04	3.00	0.80	8.00	1.20*
2.50	0.70	3.80	0.67		
3.40	0.72	4.50	0.62		
3.40	0.83	4.20	0.54		
		3.80	0.67		

Reach 4		Reach 5	
W	D	W	D
5.00	0.44	6.00	1.00*
4.60	0.58	4.50	0.70
3.80	0.52	6.00	0.80*
4.00	0.50		
3.20	0.42		
4.00	0.47		

*: estimated value

TANLLWYTH

Reach 1		Reach 2		Reach 3	
W	D	W	D	W	D
4.60	0.56	2.80	0.46	2.40	0.83
4.00	0.72	1.50	0.80	2.80	0.75
2.50	1.01	2.30	0.78	2.80	0.59
2.60	0.83	1.00	0.78	2.60	0.62
2.40	0.61	3.10	0.62	3.00	0.50
2.60	0.46	2.30	0.91	2.80	0.66
3.60	0.37			1.90	0.90
2.80	0.62			1.80	0.57
				1.70	0.52
				1.20	0.56
				1.60	0.43
				2.20	0.39

Reach 4		Reach 5		Reach 6	
W	D	W	D	W	D
1.70	0.56	2.10	0.74	2.40	0.61
3.20	0.39	1.60	0.37	2.20	0.42
1.70	0.86	2.20	0.29	1.60	0.50
2.10	0.83	3.40	0.36	4.60	0.26
2.20	0.47	1.70	0.61	4.5[illegible]	0.49
2.20	0.59	2.00	0.55	2.60	0.72
1.90	0.53				
3.60	0.23				
2.70	0.30				
2.80	0.50				

Appendix B

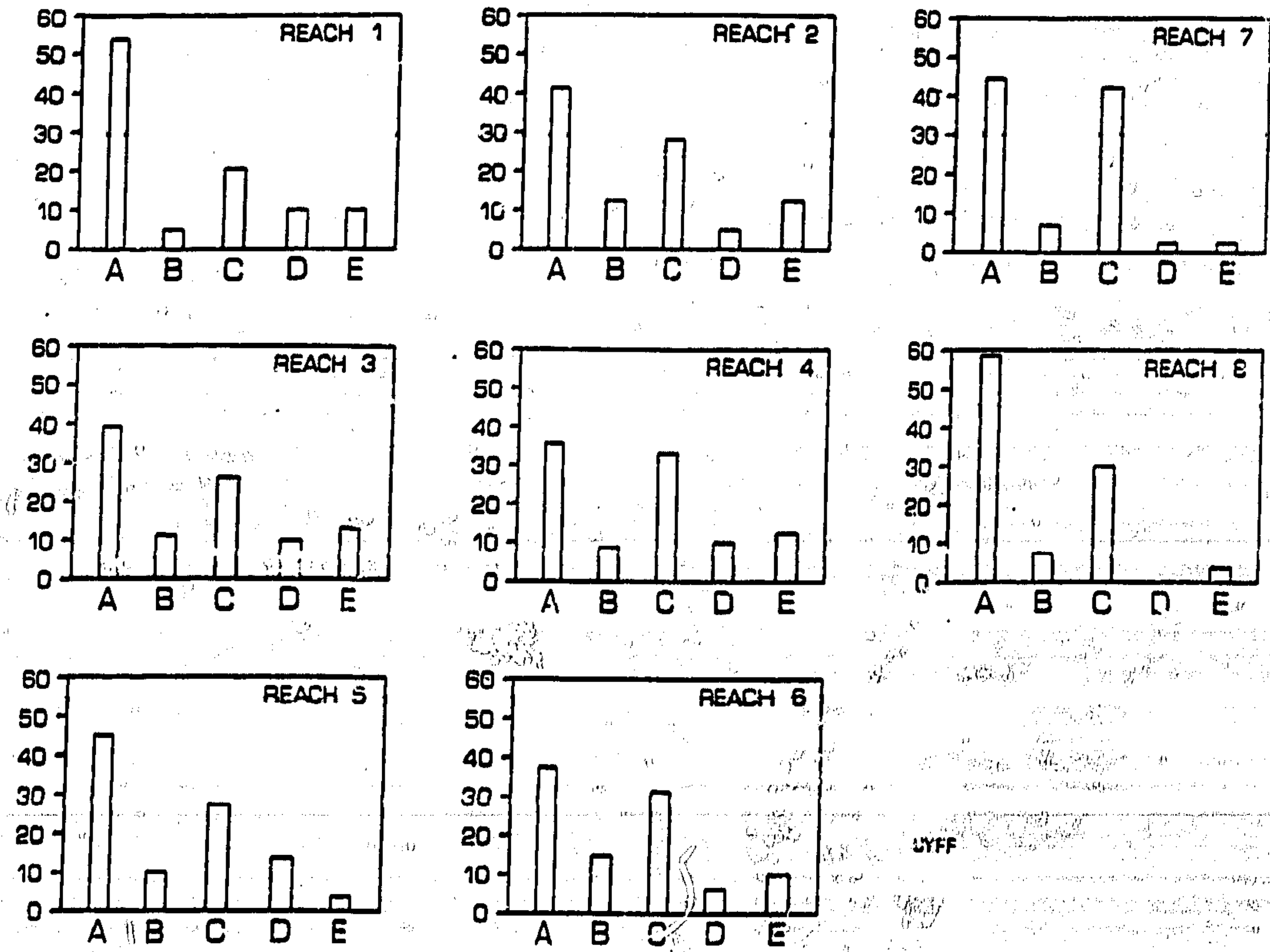
Cluster type frequency distribution (%) per reach (R)

CYFF

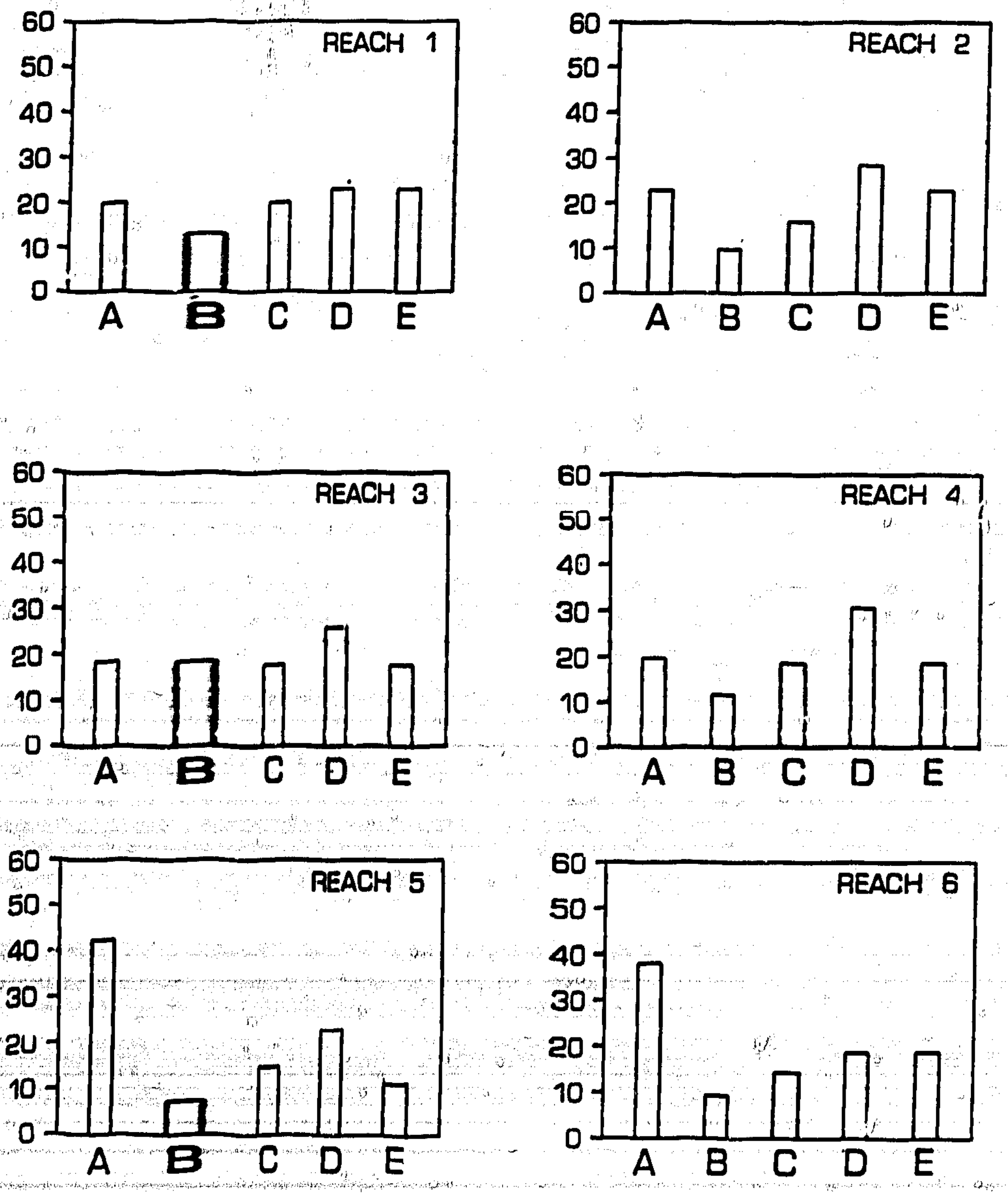
	R1	R2	R3	R4	R5	R6	R7	R8
A	54	42	39	35	45	37	44	59
B	5	12	11	7	10	15	7	7
C	21	28	26	33	28	32	43	30
D	10	5	10	10	14	6	3	0
E	10	12	13	13	3	10	3	4

TANLLWYTH

	R1	R2	[illegible]	R4	R5	R6	R7
A	21	22	17	20	42	38	33
B	13	9	17	12	8	10	0
C	21	16	23	18	15		17
D	23	28	24	[illegible]	23	19	33
E	[illegible]	25	18	18	12	19	17



Appendix B Fig.1 *Frequency histograms of the different cluster types occurring on the bed of the surveyed sediment reaches of the Cyff.*



TANLLWYTH

Appendix B Fig.2 Frequency histograms of the different cluster types occurring on the bed of the surveyed sediment reaches of the Tanllwyth.

Appendix C

Grain-size analysis of bed sediment (Phi units)

CYFF

	All data	Reach 1	Reach 2
M	- 5.47	- 5.46	- 5.66
SD	1.53	1.12	1.59
SK	0.63	1.26	0.67
KU	3.13	4.34	3.06

	Reach 3	Reach 4	Reach 5
M	- 5.07	- 5.76	- 5.43
SD	1.60	1.53	1.62
SK	0.46	0.68	0.50
KU	2.46	3.20	3.35

TANLLWYTH

	All data	Reach 1	Reach 2	Reach 3
M	- 5.68	- 5.39	- 6.49	- 6.02
SD	1.48	1.16	0.98	1.42
SK	0.57	0.01	0.24	0.41
KU	2.93	2.16	2.86	2.08

	Reach 4	Reach 5	Reach 6
M	- 5.46	- 6.01	- 5.41
SD	1.23	1.25	1.16
SK	0.22	0.29	0.43
KU	4.48	2.82	1.97

Roundness analysis of bed particles

CYFF

	All data	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
M	0.32	0.38	0.36	0.29	0.27	0.30
SD	0.17	0.18	0.19	0.14	0.13	0.17
SK	0.80	0.69	0.47	0.55	0.73	1.16
KU	3.47	3.11	2.66	3.19	3.20	4.44

TANLLWYTH

	All data	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
M	0.32	0.37	0.37	0.35	0.29	0.24	0.31
SD	0.17	0.15	0.18	0.17	0.14	0.15	0.16
SK	0.71	0.39	0.57	0.72	0.76	1.46	0.61
KU	3.21	2.37	2.39	3.30	3.17	6.24	3.53

Spericity analysis of bed particles

CYFF

	All data	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
M	0.50	0.46	0.49	0.50	0.53	0.50
SD	0.14	0.12	0.14	0.15	0.14	0.13
SK	0.40	0.51	0.52	0.28	0.29	0.39
KU	2.71	3.07	2.83	2.55	2.67	2.46

TANLLWYTH

	All data	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6
M	0.49	0.46	0.46	0.51	0.51	0.48	0.48
SD	0.12	0.12	0.10	0.13	0.12	0.13	0.11
SK	0.39	0.19	1.01	0.32	0.34	1.58	0.02
KU	2.78	2.61	3.62	2.61	2.79	2.89	2.28