Bedload dynamics and abrasion at the Plynlimon catchments, mid-Wales: the effects of new forest management practice

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Contents

Abstract

This thesis reports the bedload transport characteristics of two small upland streams on Plynlimon, mid-Wales. The Nant Tanllwyth is a small upland channel undergoing a period of land use change and the Afon Cyff is an open moorland catchment previously used as a control in paired catchment studies. In accordance with forest guidelines, an ecologically centred approach to timber harvesting was undertaken in the Nant Tanllwyth. Measures included the removal of brashings from near watercourses, hand felling proximal to the main channel and using brash matting to protect soils from heavy mechanical operations.

Bedload transport characteristics were monitored by measuring trapped sediment in end of channel bedload traps, whilst tracing various sizes of magnetically tagged clasts through the channels. Over a two-year period, the sediment fluxes in both the harvested Nant Tanllwyth and in the nearby Afon Cyff were examined. Measured bedload yields by trapping were 0.91 t km^2 yr^{-1} in the Afon Cyff and 7.47 t km^2 yr^{-1} in the Nant Tanllwyth. Analysis of historical records showed that in both channels bedload yields had decreased more than six-fold since the 1970s. Bedload trap data showed differences between the two channels in their response to threshold streamflow. The Nant Tanllwyth showed a clear linear relationship between bedload outputs and streamflow over a 0.3 m^3s^{-1} threshold, whereas the Afon Cyff demonstrated more variability around its linear response to threshold events.

Tracer results underline this difference between the channels and demonstrate the stochastic nature of bedload transport in both reaches. Mean travel distances of all clasts were 39.74 m yr^{-1} and 27.26 m yr^{-1} in the Nant Tanllwyth and Afon Cyff respectively. Whilst a probability function for tracer travel distance for any individual clast or size range is not provided, size selectivity of smaller clasts is shown in both reaches and mean travel distances correlate significantly with streamflow thresholds.

The decrease in bedload yields in the undisturbed Afon Cyff since the 1970s is attributed to the effects of a previously unreported dam-break in the upper reaches of the catchment. This feature has significant implications for the use of the Afon Cyff in future paired catchment studies. Decreases in bedload yields in the Nant Tanllwyth are attributed to the further stabilisation of ditches and soils under mature forestry.

Abrasion of clasts is controlled primarily by travel distance rather than abrasion in place, but abrasion levels in both channels are not seen as an important determinants of total bedload yield.

Evidence presented suggests that in the short term, new forestry practices have reduced the impacts of harvesting on bedload flux. Little disturbance of the stream channels or banks took place within the study and although tracer clasts moved slightly further during the post-harvest phase, yields from the Nant Tanllwyth bedload trap remained unaltered. This discrepancy is thought to represent the bedload trap's inherent lag monitoring change.

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Section 1: Introduction

Bedload transport in gravel bed rivers is controlled by both the hydrological and sedimentological parameters in the surrounding catchment. This thesis will examine the way in which timber harvesting of plantation forestry affects these parameters and subsequently changes the nature of coarse bedload flux in a small mountain stream.

1.1. The issue: clearfelling of plantation forests and its effect on upland streams

Changes in upland bedload yields can affect both channel morphology and downstream landforms and flow parameters, in turn these can impact on the ways in which river channels and their water yields are used as a resource. Channel instability problems are demonstrated on the Afon Trannon a 72 km^2 catchment in mid Wales where Leeks *et al.* (1988) found changes in upstream engineering affecting downstream channel erosion. The magnitude and distribution of bedload yields also affect the spawning of fish (especially salmon) due to infilling of the sediment matrix (Lisle and Lewis, 1992) and hence spawning beds (Maitland *et al.*, 1990; Bellamy, 1992). There are also possible implications for reservoir infilling (Lovell *et al.*, 1973; Duck and McManus, 1987) where supply capacity is reduced.

To date few data are available from which we can assess the impact of upland plantation forestry on the mechanics of bedload flux. The UK studies which have reported the effects of forest land use on bedload yields do not show a consistent trend. Indeed, the extent of changes in bedload yields due to forest activities has shown considerable variation. Bedload changes include a 40% increase in bedload at Balquhidder (Blackie and Newson, 1986; Ferguson and Stott, 1987; Johnson, 1993) in the forested Kirkton catchment. Numerous studies demonstrate decreases in the medium term coarse sediment outputs due to the effect of debris jams (Hedin *et al.*, 1988; Whitaker, 1992; Assani and Petit, 1995). Painter *et al.* (1974) highlighted the difficulty of accounting for the large number of variables affecting bedload experiments. Leeks (1992) examined the effects of the forest rotation on suspended and bedload yields and showed that delivery of sediment was from "catchment surface, drains and tracks" with the surface area damaged by forwarders and skidders. Bedload yields in the Plynlimon catchments were reported by Moore and Newson (1986) with the afforested Nant Tanllwyth giving yields of 38.4 t km^{-2} yr^{-1} and moorland Afon Cyff 6.1 t km^{-2} yr^{-1}. At Balquhidder, Central Scotland, Ferguson *et al.* (1987) reported 9 fold increases in bedload yield of the Kirkton catchment after felling, with pre-harvest yields of 56.6 t km^{-2} yr^{-1} and post-harvest yields increasing to 462.8 t km^{-2} yr^{-1}. In the Loch Ard catchment, Central Scotland, Ferguson *et al.* (1991) showed a doubling in suspended sediment outputs following clearfelling of 85 % of the catchment from 1 to 2 t km^{-2} yr^{-1}.

The importance of understanding the role of forestry in bedload transport characteristics is underlined by the changing land use in the United Kingdom. Table 1.1 shows the changes in forest cover in the United Kingdom since 1980. Total forest cover has increased by 18% since 1980/81 and the increase in area of broadleaf by around 16% between 1985/86 and 1996/97 following introduction of grant schemes to encourage new planting.

Table 1.1. Forest cover in the United Kingdom since 1980/81

Year	Coniferous woodland '000 Ha	Broad-leaved woodland '000 Ha
80/81	1430	691
85/86	1520	781
90/91	1582	830
94/95	1581	890
95/96	1585	901
96/97	1597	907

Source: The environment in your Pocket. The Department for the Environment, Transport and Regions (1998) HMSO

Bedload fluxes have been demonstrated to vary both spatially and temporally, with a number of discrete mechanisms (over and above the relationship between discharge and transport) governing the nature of bedload transfer over the short, medium and long terms. These include mechanisms, such as the propagation of sediment slugs (Nicholas *et al.*, 1995), changes in the nature of sediment sources (Burt *et al.*, 1983), adjustments to bed armour (Gomez, 1983) and changes in overall hydrology (Johnson, 1991).

Changes have recently taken place in the UK in forest clearance practices. In the past, aerial cableways have been used on steep terrain to extract timber from steep slopes to roads and clearings where it was loaded onto lorries. On shallower slopes, heavy machinery such as forwarders were previously used. Modern clearfelling practices utilise *'one machine'* operations, where a single machine called a timber harvester can drive into the forest, cut down trees, strip brashings and chop whole trees into logs in a single action. In addition, rather than harvesting a whole catchment, plot-scale harvesting is now commonly undertaken to minimise disturbance and harvesting is timed to avoid long periods of heavy rain and run off. The introduction of this machinery, the practice of laying down brash matting and the use of buffer strips around water courses has increased the need for a re-examination of the effects of forest operations on bedload transport. The technical recommendations for current forestry practice are included in the publication Forest and Water Guidelines (1993).

To successfully examine the significance of modern forest clearance on bedload transfer, the first requisite is for a process-based study of bedload transfer, ascertaining the nature and pattern of sediment transfer before and after felling operations.

1.2.1. The history and extent of forestry in the UK

Since the realisation during the First World War that the nation's timber resources were limited (Blackie and Newson, 1986), Britain has embarked on a major policy of afforestation to supply the demand for timber. In 1980 Britain imported 92% of its timber resources (Newson and Calder, 1980) and the government committed to doubling its resource base, with a further 3 million ha of development planned. Approximately 11.5% of Wales is under commercial forest cover (Omerod *et al.* 1987)

Conversion to plantation forest has been and continues to be, the biggest change of land use in the UK, peaking in the 1970s with 40,000 ha yr^{-1} of planting (Robinson and Blyth, 1982). The majority of this development has taken place throughout the upland areas of North and West Britain (Binns, 1979, 1986; Newson and Calder 1980), land traditionally of the lowest quality. These areas are also associated with the highest rainfall totals and are consequently the water supply regions of the UK.

Historical patterns of afforestation in England, Scotland and Wales have differed slightly, with the respective peak of planting occurring in England in the period 1955-59 (12 000 ha yr^{-1}). In Scotland the peak was in the period 1970-74 (35 000 ha yr^{-1}), and in Wales during the period 1960-64 (6 000 ha yr^{-1}) (Omerod and Edwards, 1985). With planting times largely controlled by political and economic conditions, a disparity exists in the extent and pattern of clearfelling required. The major increase in the requirement of clearfelled land in Wales is therefore associated with the tremendous increase in planting occurring during the 1950s and 1960s in Wales (6000 ha yr^{-1} in Wales alone). Only a small percentage of timber planted this century has been harvested (Stott, 1987) and harvesting will increase further the maturing of current forest cover.

1.2.2. The implications for water users.

The derivation of water from uplands in the UK is important since a large percentage of domestic and industrial supplies flow from upland catchments. Water suppliers traditionally favoured forestry as cover for water supply catchments in the UK (Leeks and Roberts, 1987) believing forests to provide protection against pollution and soil erosion (Cuthbertson, 1948). However, with the work of Law (1956) highlighting changes in hydrology and Newson (1980a) showing changes in coarse sediment outputs, the impact of commercial forestry on water users has become increasingly spotlighted.

Reported effects of increased sediment supply and changing sediment regimes are numerous and include the impacts on fisheries, morphology and reservoir capacity. Studies on fisheries (Harriman and Morrison, 1982; Stoner and Gee, 1985; Carling and Orr, 1990; Bellamy, 1992) have concentrated on the adjustment of sediment distributions of surface river gravels as changes in the near surface matrix affect Salmon spawning success. The impact on downstream river morphology (Bilby, 1984; Carling, 1988; Newson, 1986; Newson and Leeks, 1987) and the changes in reservoir capacity

(Stretton, 1984, Duck and McManus, 1987) are also possible consequences of changes in sediment supply. Significant research has been undertaken in North America (Grant and Wolff, 1991; Ursic, 1991) and New Zealand (O' Loughlin *et al.*, 1980) to establish the effects of forest clearance on sediment transport, though little research has been undertaken on how the new harvesting techniques might impact on bedload considering the specific climatic and geomorphic conditions of the United Kingdom.

1.2.3. The implications of new technologies and techniques

New techniques for forest-clearance are now widely practised, including the one-machine operations now in use at Plynlimon. Previous work on the effects of forest operations on water resources (Haupt and Kidd, 1965; Ferguson and Stott, 1987) may be of limited value as these studies were based on different practice and technology. Stott (1997b) states that harvesting in previous years was generally undertaken with chainsaws and aerial runways, but personal observations now suggest that the major erosive damage associated with these methods might now have been limited by the techniques now used by forest operators regarding water management (Forestry Commission, 1993).

It is now appropriate to examine the effects of the implementation of these techniques. Not only are some previous experiments associated with outdated harvesting machinery, but consideration of the results of previous studies has prompted a more ecologically-centred harvesting philosophy, using environmentally sensitive plot-scale (as opposed to catchment-scale) harvesting.

1.2. The research gap

Although some research into bedload transport in forest catchments has been undertaken, a number of areas are either under-developed, do not include the felling phase of the forest rotation, or have not used modern techniques to examine potentially subtle changes in bedload output. The areas outlined overleaf are identified as areas where opportunity exists for further investigation:

1 Bedload tracers, whilst proven as an aid in understanding bedload transfer, have not been used in conjunction with forestry land use change;
2 tracers have not been used in conjunction with bedload traps as a method for independently assessing flux in the same channel, and
3 forest clearance mechanisms are changing, with plot-scale harvesting practice undertaken in the United Kingdom and new timber harvesting technology in place and have not yet been investigated.

1.3. Thesis development

1.4.1. Project Aims

In order to attempt to address the research opportunities above and to direct the research work, a set of aims were formulated early in the project. They are listed below, and will be addressed in the discussion and conclusions in sections 5 and 6:

1 *To ascertain the effects of a change in land use in one catchment on the bedload characteristics of the main channel using a traditional paired catchment study;*

2 *to take an holistic approach to bedload transport, in studying total flux, size distribution and individual grain dynamics in the natural environment;*

3 *to assess how changing sediment production regimes affect the nature of bedload transport, and*

4 *to examine how forest operations can be improved further to minimise the impacts of timber-harvesting.*

1.3.2. Thesis structure

This introduction aims to set out the problem, rationalise a possible hypothesis and set out the aims of the project. The literature review (Section 2), will examine the issues of forestry, the mechanics of sediment transport and discuss the previous use of tracers in fluvial geomorphology. Section 3, Methodology, will describe the monitoring of hydrological variables and the design and implementation of tracing and trapping programmes to establish the bedload regimes for the two channels. In the Section 4, Results, the flow data for the experimental period is analysed and related to bedload trap data and tracer travel distances. The discussion will consider if the partial clearfelling of the Nant Tanllwyth catchment in April 1996 affected the transport characteristics (both flux dynamics and total load) of the Nant Tanllwyth and examine these results with reference to the Afon Cyff. It will also consider the changes in catchment outputs since the study by Moore and Newson (1986) and Leeks (1992).

1.4. Field sites

1.4.1. Selection Criteria

Field sites were required to test out the hypothesis and aims of the project outlined and discussed above. Sites were required that specifically satisfied the logistical, financial and scientific constraints of the project. The major requirements identified for suitable field sites are listed below:

1 An upland afforested area, with a stream network with measurable bedload flux;

2 a catchment undergoing harvesting of a significant portion of its area;

3 the availability of hydrometric instrumentation to monitor streamflow;

4 the availability of a paired catchment to provide control in the experiment, and

5 accessible driving distance from Liverpool John Moores University.

The project required catchment sites that could be characterised in terms of their geomorphological and hydrological parameters prior to a time of land use change. It was therefore necessary to have a suitable time to monitor both catchments and quantify total sediment fluxes under a range of flows and conditions. A relatively active pair of channels was deemed necessary, as in streams exhibiting low sediment discharges, any changes due to felling might prove difficult to quantify in the short to medium term. The consent and co-operation of relevant forest management was needed to confirm the time of felling and this was available at the Plynlimon catchments. The Plynlimon catchments also offered an unparalleled suite of data, both historic and current, including streamflow, meteorological and long-term sediment records.

The use of a paired catchment study was important to the aims of the project, with paired catchments providing a useful tool in geomorphological investigation (Moore and Newson, 1986). It was intended that the use of a control, in conjunction with the changing catchment, would provide an additional tool for disentangling data from the many environmental factors that would inevitably influence the results, particularly in terms of extreme events. The catchments needed to be similar in physiographic, hydrologic and meteorological characteristics.

Finally and crucially, with the project's financial and logistical constraints, a location was required that allowed easy access from Liverpool. Access had to allow trips to be undertaken with the minimum of notice, permitting fieldwork to be carried out soon after flood events, during good weather or with available field staff.

1.5. The Plynlimon Catchments

The Plynlimon catchments are located on the spine of the Cambrian Mountains in mid-Wales, in the headwaters of the Rivers Wye and Severn. The primary research areas were the channels of the Nant Tanllwyth and Afon Cyff, headwater streams of the Rivers Severn and Wye respectively. With the consent and co-operation of the Institute of Hydrology, it was possible to use the Plynlimon research catchments and associated instrumentation (Newson, 1976; Kirby *et al.*, 1991). The catchments have been operational since 1968 and now maintain intensive hydrology, water quality and sediment monitoring networks (Leeks and Roberts, 1987; Leeks, 1992; Stott and Marks, 1998). The stream channels are influenced by both the local hard rock geology, which is Ordovician and Silurian mudstones and shales and glacially derived cobbles and boulders. Much of the bedload is made up from this material and reworking of fluvio-glacial material of similar composition. Table 1.2 below lists various physical characteristics of the stream channels and Figure 1.1 is a location map of the Plynlimon catchments, showing their basic drainage network and location of experimental channel reaches. Plate 1.1 is a view of the forested Nant Tanllwyth channel reach before timber-harvesting operations began. Plate 1.2 shows a section of the Afon Cyff experimental channel reach at the start of the project. No major land use change occurred within the Afon Cyff catchment during the field study period.

1.5.1. Catchment characteristics

The basic catchment characteristics are summarised in Table 1.2 below. With clearfelling taking place adjacent to the channel banks in the Nant Tanllwyth, timber-harvesting activity was expected to manifest itself on sediment production sources both within the main channel as well as in the surrounding catchment areas. Further details on channel characteristics are given in section 1.6.2. Data in Table 1.2 reproduced from Newson (1976, 1980a) is indicated .

Table 1.2. Physical Characteristics of the Plynlimon Catchments

Measurement	Units	Nant Tanllwyth	Afon Cyff
Physiographic characteristic			
Catchment area *	(km^2)	0.89	3.13
Altitude range	(m)	350 - 570	360-560
Land use		Forestry	Moorland
Drainage density *	km km^{-2}	2.5	1.9
Mainstream length *	km	1.9 (3.3 including drains)	2.9
Overland slopes * (0-9°)	%	69.4	47.5
(10-19°)		30.6	52.5
Channel gradient *	m km^{-1}	58.2	79.4
Stream flow (1980-1990)			
Mean	m^3s^{-1}	0.066	0.20
Max	m^3s^{-1}	2.66	6.07

** Reported in Newson (1976, 1980a)*

The Nant Tanllwyth catchment area is approximately one third that of the Afon Cyff. This difference is reflected in the mean and maximum streamflow that the channels produce. Mean flow during the 1980s in the Afon Cyff (0.07 m^3s^{-1}) is approximately three times that of the Nant Tanllwyth (0.20 m^3s^{-1}) and maximum flow is over twice as high (6.07 m^3s^{-1} and 2.66 m^3s^{-1} respectively). Further analysis of flow thresholds in the channels is given in section 4.1. The Tanllwyth has a similar range in altitude to the Cyff and both bedload traps are at 360 m A.O.D.. Land use in the Nant Tanllwyth is commercial forestry with its forest boundaries extending through the entire catchment. Main channel length is shorter in the 1.9 km Nant Tanllwyth with the Afon Cyff one km longer; effective drainage density is greater however in the Nant Tanllwyth than in the Afon Cyff. Drainage density is greatly affected by the existence of forest drainage ditches in the Nant Tanllwyth, which nearly doubles its drainage density. Newson and Harrison (1978) however, highlight the effects of piping and peat throughflow as being particularly important in the moorland Afon Cyff catchment. Greatest catchment slope angles are found in the Afon Cyff, with over 50% of the catchment having slopes greater than 10°. A similar index in the Nant Tanllwyth shows only 31% in this range. Both streams are of a pool-riffle type, exhibiting areas of channel where bedrock is exposed, as well as areas where accumulations of sediment up to 0.5 m deep predominate. The Afon Cyff has greater areas of flat, smooth bedrock and where this is the case, the bedrock is significantly smoother than the broken shale beds of the Nant Tanllwyth.

A location map of the Plynlimon catchments is shown in Figure 1.1 below, with forest cover shaded. Locations of bedload traps and experimental channel reaches are also indicated. Descriptions of each catchment are given individually below.

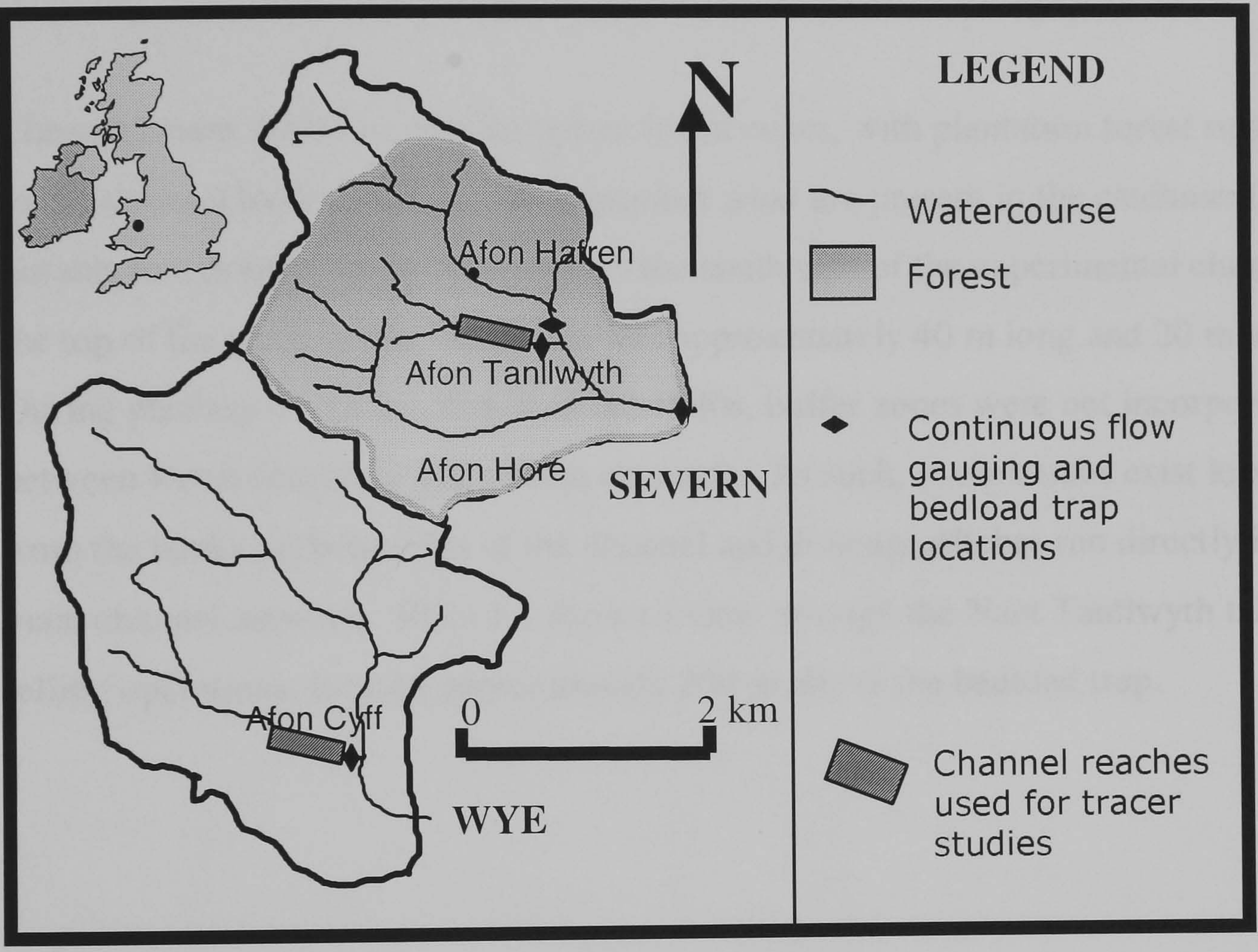


Figure 1.1. Map of Plynlimon experimental catchments

NANT TANLLWYTH

The Nant Tanllwyth sub-catchment is set between two larger catchments, which are also utilised for commercial plantation forestry. To the North is the Hafren catchment, officially the source of the River Severn. The Hafren has been the subject of several studies into the effects of afforestation on sediment and hydrology (e.g. Newson and Harrison, 1978) as well as the effects of afforestation on fish populations (Crisp *et al.*, 1980). To the south, the recently felled Afon Hore was studied by Leeks (1992) with reference to the impact of commercial forestry on sediment dynamics.

The catchment itself has near complete forest cover, with plantation forest running right to the channel banks. Very small unplanted areas are present in the catchment, most notably in a poorly drained flat area on the south side of the experimental channel and at the top of the study reach. This area was approximately 40 m long and 20 m wide. During planting of the catchment in the 1940s, buffer zones were not incorporated between forest boundary and stream channels. As such, mature trees exist less than 1 m from the banks on both sides of the channel and drainage ditches run directly into the main channel network. Plate 1.1 shows a view through the Nant Tanllwyth taken before felling operations, located approximately 200 m above the bedload trap.

Plate 1.1. The Plynlimon Catchments: Nant Tanllwyth prior to timber harvesting

Figure 1.2 shows the harvesting regime of the Nant Tanllwyth, indicating the direction of timber extraction and the order in which areas were harvested.

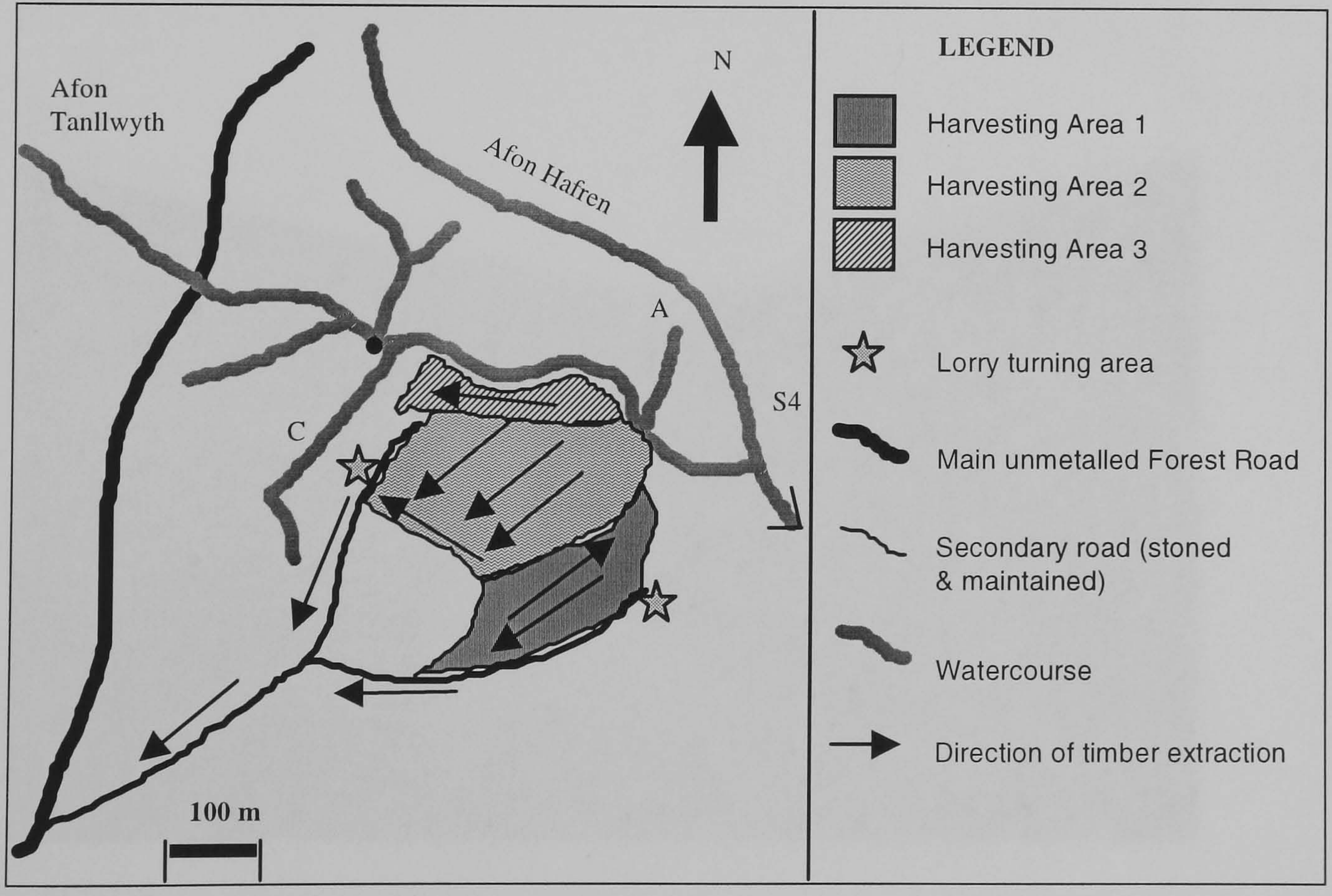


Figure 1.2. Harvesting regime of the Nant Tanllwyth catchment

AFON CYFF

The Afon Cyff catchment lies 4 km to the south west of the Nant Tanllwyth and is a 3.12 km^2 open moorland catchment. Land is used for sheep grazing, though a track runs through the lower portion of the catchment that is used for the testing of rally touring cars. Field observations suggest that small sediment inputs might derive from debris from this track thrown into the stream network by passing high-speed vehicles. The existence of a nineteenth century lead mine in the upper reaches could potentially change catchment drainage characteristics, but otherwise there are no artificial changes to the catchment drainage network. During summer 1999, the presence of an old dam (Hill, pers comm) was also discovered in the upper catchment, the structure is thought to date from the nineteenth century. Studies by Newson (1976) and Newson and Harrison (1978) make further reference to the catchment details. A view of the lower portion of the Afon Cyff catchment is shown Plate 1.2 below. The furthest point of the channel visible being the steepest section of the experimental channel used in the study.

Plate 1.2. The Plynlimon Catchments: Afon Cyff

1.5.2. Channel characteristics

CHANNEL DIMENSIONS

Characteristics of the experimental reaches shown in Figure 1.1 are highlighted in Table 1.3.

Table 1.3. Physical Characteristics of the experimental channel reaches

	Length	Mean channel slope	Mean thalweg depth
	m	%	m
Nant Tanllwyth	397	5.4	0.08
Afon Cyff	327	4.5	0.16

Both experimental channels reaches end at the pre-installed channel bedload traps near the confluence point of their source channels: the River Wye in the Afon Cyff and Afon Hafren (River Severn) for the Nant Tanllwyth. The Nant Tanllwyth experimental channel is some 21 % longer than the channel of the Afon Cyff. By examining the gradients of entire channel lengths (see in Table 1.2), the Afon Cyff is considerably steeper than the Nant Tanllwyth. Examining gradients of just the small experimental sections reverses this trend, with the Nant Tanllwyth being slightly steeper. Mean thalweg depth of the Afon Cyff is double that of the Nant Tanllwyth. This can be attributed to the larger pools within the channel and two significant falls within the study reach.

BEDLOAD GRAIN SIZE DISTRIBUTION

Methods for determining grain size distributions are discussed in section 3. To place the study in context, approximate grain size distributions are given below for each experimental channel.

Nant Tanllwyth

Figure 1.3 shows the approximate grain size distribution for the surface material in the Nant Tanllwyth. These were determined using Wolman counts at random exposed points in the channel. Figure 1.4 shows a more detailed sub-surface distribution obtained by a series of freeze core samples taken during the project. Freeze core data shows only clasts below 64 mm.

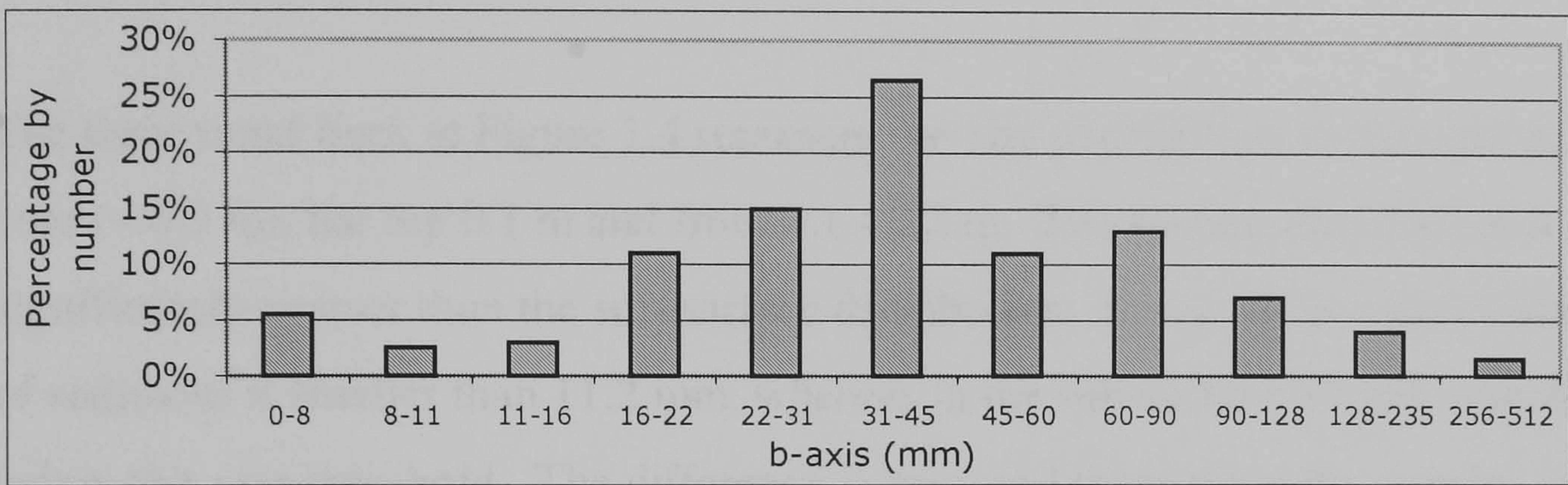


Figure 1.3. Surface grain size distribution of Nant Tanllwyth channel bed

Using a Wolman based counting method, the median b-axis of clast in the Nant Tanllwyth falls in the 32-45 mm category, with long tails either side of the median. The method uses a counting strategy, so the median represents the number of clasts rather than a median derived by mass (sieving). It was decided that this was the best way to attempt to make a tracer distribution, as due to technical difficulties, tracers could not be manufactured to represent all parts of the size distribution. The method did create problems in measuring small gravels, and was particularly susceptible to error in determining sites to chose for sampling.

To augment this surface sample, sieving of samples obtained by freeze coring was undertaken in conjunction with the Institute of Hydrology and these data are shown below in Figure 1.4. Full details of this method are given in section 3.

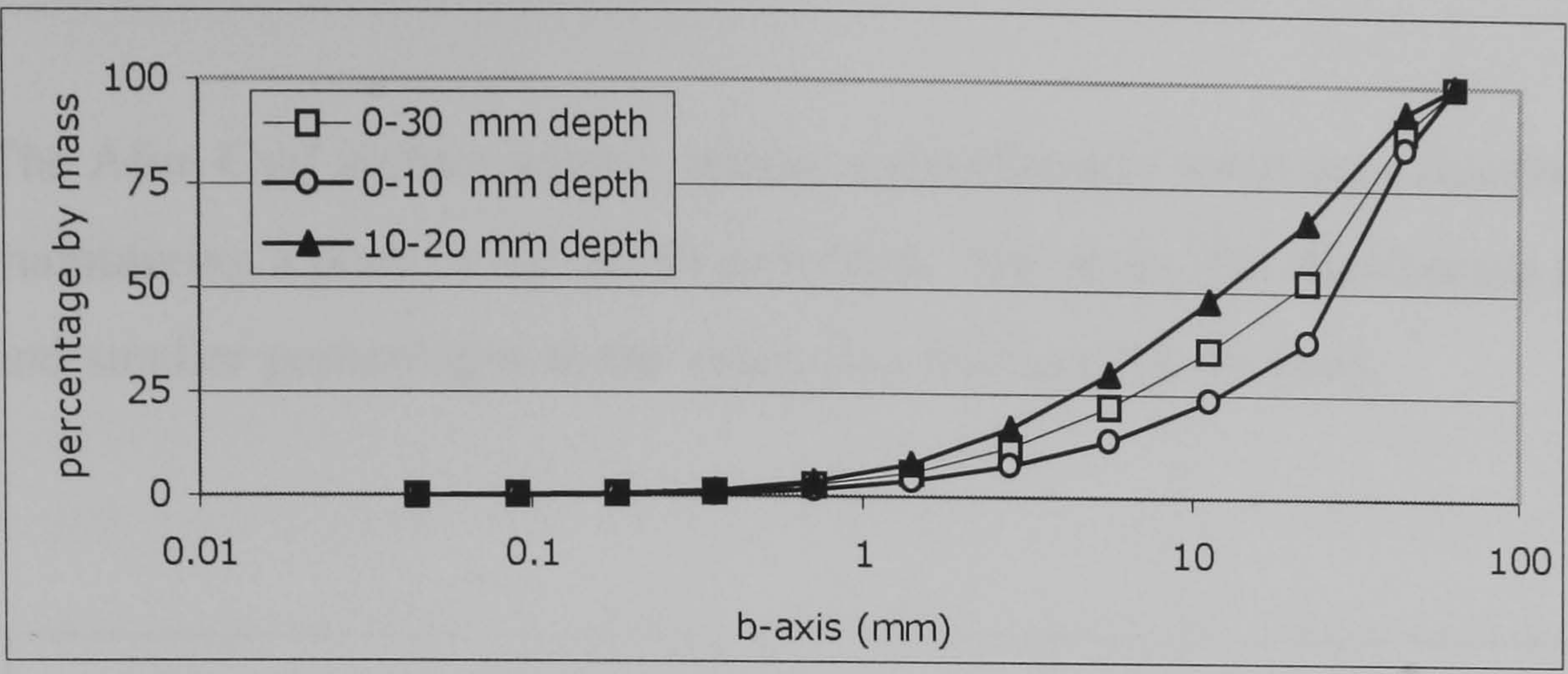


Figure 1.4. Freeze core derived sub-surface distribution of the Nant Tanllwyth channel bed

The three trend lines in Figure 1.4 represent the size distribution in the total depth of core (~ 0.3 m), the top 0.1 m and from 0.1 - 0.2 m. The surface distribution is significantly coarser than the sub-surface distribution. In the surface distribution 24 % of sediment is smaller than 11.2 mm, whereas in the sub-surface distribution 48 % is below this size threshold. The difference is mirrored throughout the smaller size intervals of the distribution.

Afon Cyff

Figure 1.5 shows the approximate grain size distribution for the surface material in the Afon Cyff. These were also determined using surface counts. Again, this is followed (Figure 1.6) by a more detailed examination of the substrate obtained from freeze core samples.

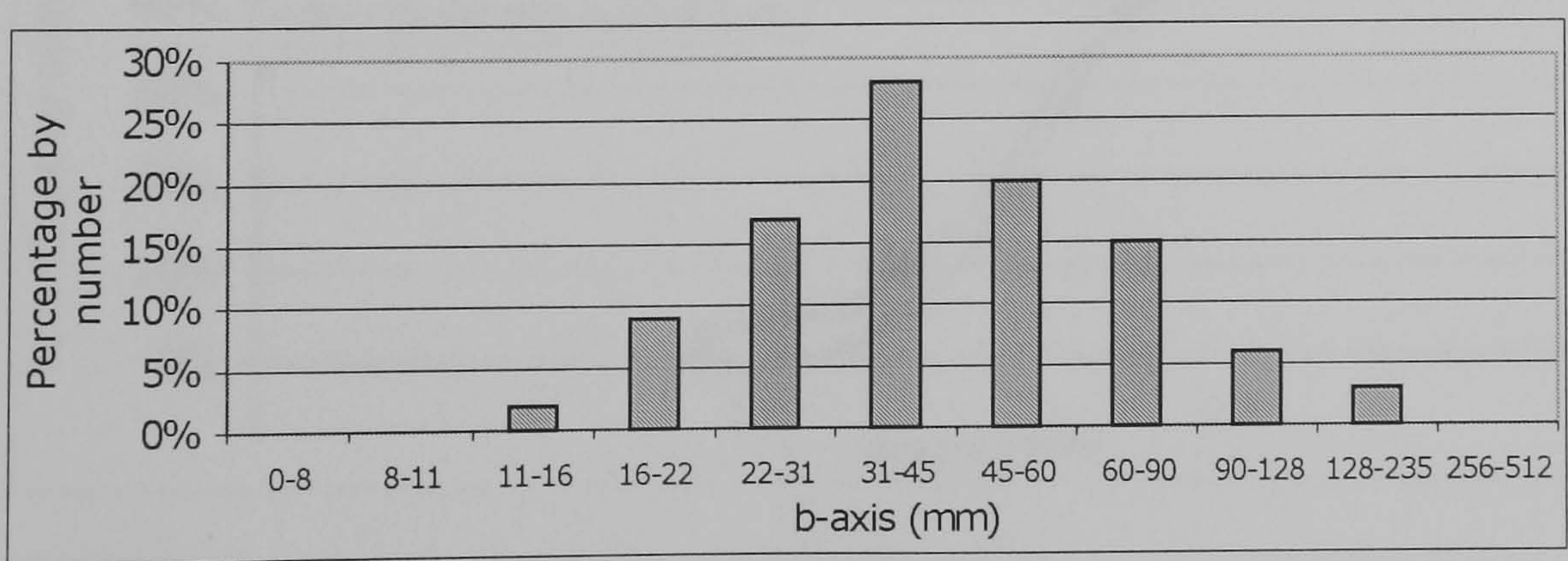


Figure 1.5. Surface grain size distribution of Afon Cyff, derived from surface counts

The Afon Cyff surface sample shows a significantly more even distribution, maintaining a peak in the 32-45 mm class. However, the distribution has shorter tails, and smaller percentages in the small size fractions (8-16 mm).

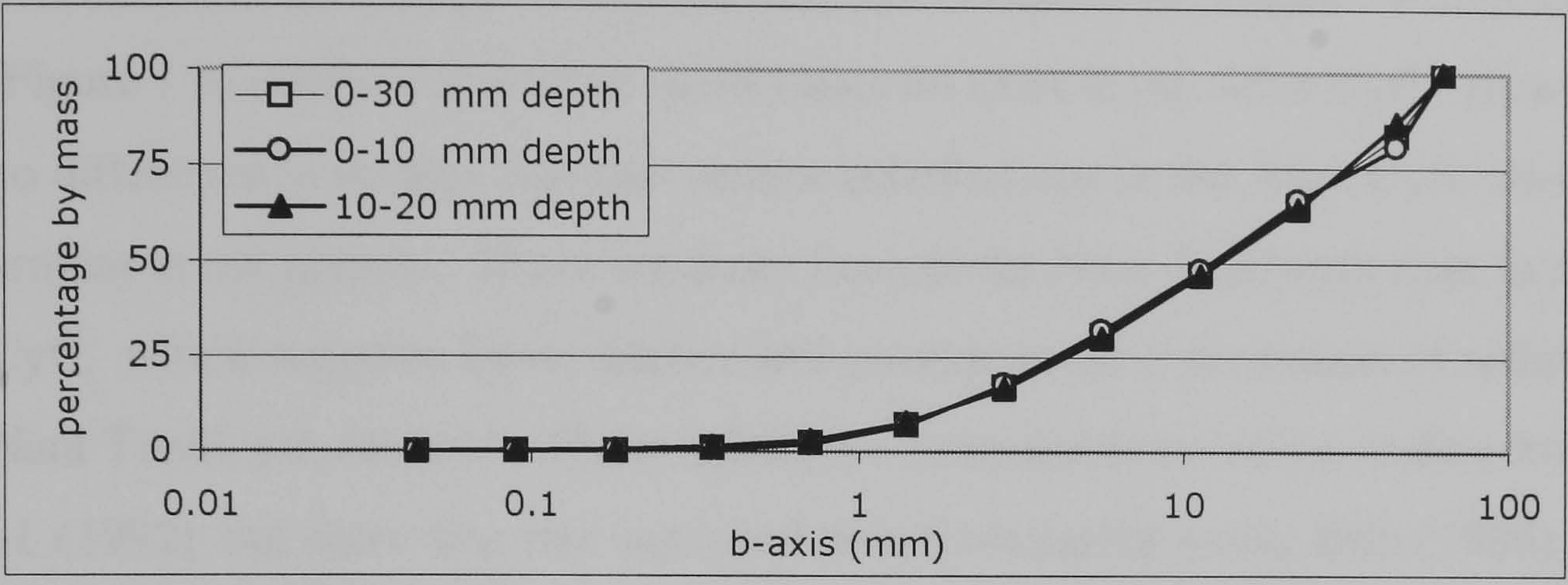


Figure 1.6. Freeze core derived sub-surface size distribution of the Afon Cyff

The subsurface freeze core samples for the Afon Cyff (Figure 1.6) show a different pattern to the Nant Tanllwyth. There is little difference in the samples from different depths, suggesting that a vertical sediment gradient does not exist in the Afon Cyff, and that is well mixed.

Comparisons of both channels

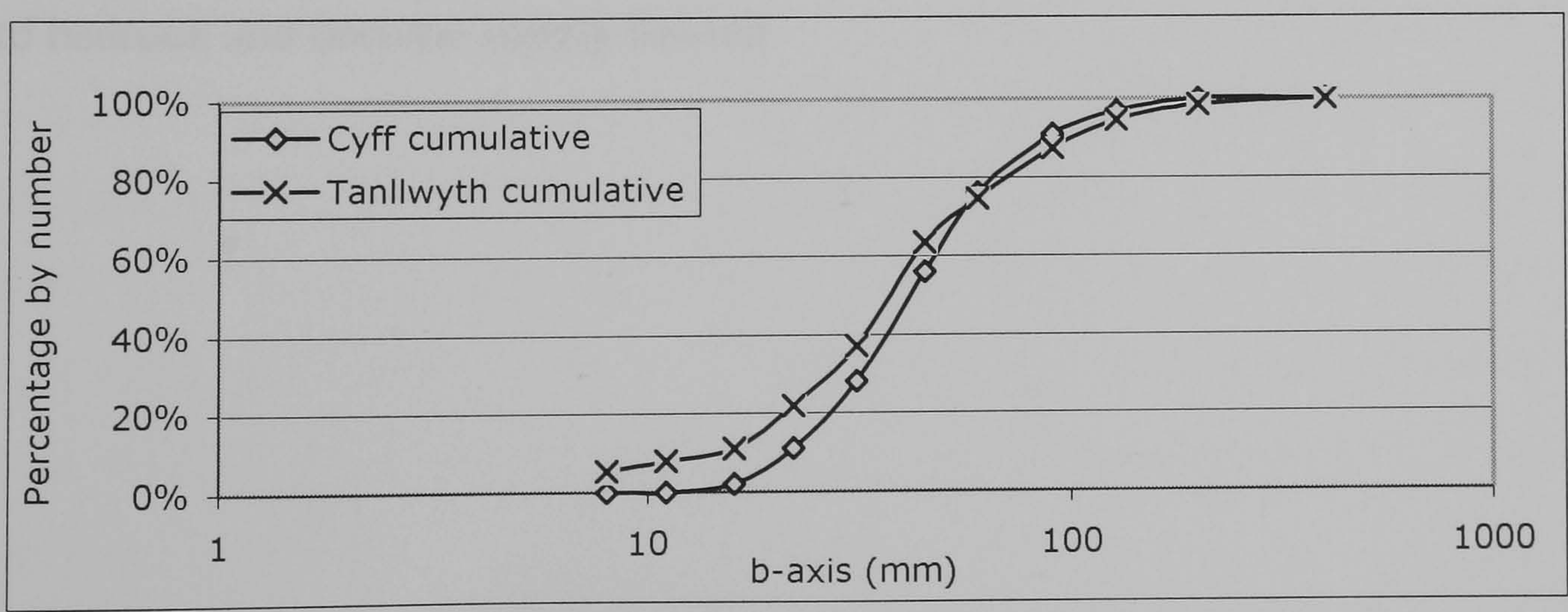


Figure 1.7. Comparisons of size distribution based on surface counts in Nant Tanllwyth and Afon Cyff

The size distributions of the two channel's surface samples (Figure 1.7) show curves of slightly different shapes and demonstrate a coarser distribution in the Afon Cyff, exaggerated in the largest size categories. In the surface samples no sediment in the smallest size ranges is found in the Afon Cyff which could highlight either measurement deficiency, or alternatively the existence of armour. Freeze core data (Figure 1.6) confirm that these small clasts do exist in the Afon Cyff. However, there is no difference in surface and sub-surface distributions in the Afon Cyff, which suggest armour is not present. There are more fines in the Nant Tanllwyth than in the Afon Cyff, which suggests forest ditches still provide some contribution of sediment to the Nant Tanllwyth channel. These results are comparable to recent studies from Brewer *et al.* (1992) but show less fine sediment than from earlier work. Billi (1986) showed that the bedload size distributions of the two streams were alike using surface samples. Similarly to this study, the variation in samples between bedload traps, bulk samples and sub-surface sediment in the Nant Tanllwyth showed a greater proportion of fines. Arkell *et al.* (1983) showed the high volume of fines entering from two surveyed ditch systems in the Nant Tanllwyth. The increased frequency of fines in the Nant Tanllwyth was attributed to the existence of these forest ditches throughout the catchment, some of which were heavily eroded.

Forestry ditches still make a contribution to the sediment load and grain size distribution of the Nant Tanllwyth, though due to the flushing out of sediment (which, as observations in the Nant Tanllwyth show is frequent) drainage ditches have been eroded to bedrock and become supply limited.

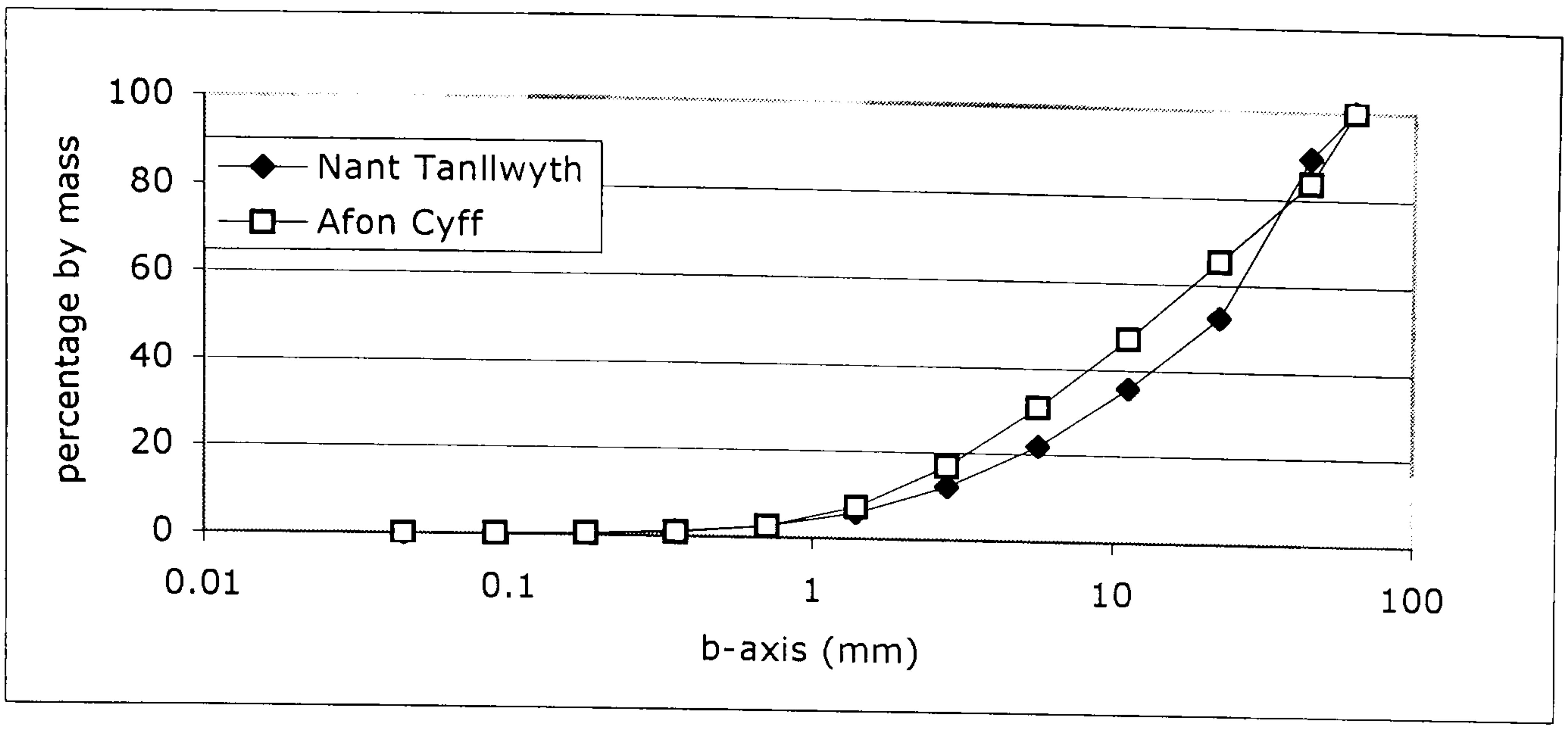


Figure 1.8. Freeze-core grain size distributions in the Nant Tanllwyth and Afon Cyff

The distribution of the bed in the Afon Cyff is finer in the smaller size ranges, but in the largest sizes, the Nant Tanllwyth has a coarser distribution.

BEDLOAD SHAPE DISTRIBUTION

Shape plays a potentially important, though often secondary role in determining travel distance. If shape distributions from the two channels had been significantly different, further analytical problems would arise. In addition, shape may govern abrasion rates by breakage of clasts occurring more readily on thin or angular gravel. However, bedload shape distribution in both channels was found to be almost identical (also seen in Billi) and the distributions are shown below of Zingg (Figure 1.9) and Krumbein (Figure 1.10) analysis. Zingg analysis was chosen to give a clear descriptive indication of the shape distribution of the two channels, along with providing a set of values to compare with notable previous work (Ergenzinger, 1992). The Zingg classification also provides an objective measure of particle form (Briggs, 1977). The Krumbein sphericity index provided a more convenient assessment for statistical analysis in terms of its analysis providing an output between 0 and 1, though in reality most particles fall between 0.1 and 0.9.

For shape distribution, clasts large enough to be fitted with magnets for tracing purposes were selected at random and measured. The Zingg distribution showed a large skew towards blades and discs, with few rods and spheres present. This can be easily attributed to the nature of the geology.

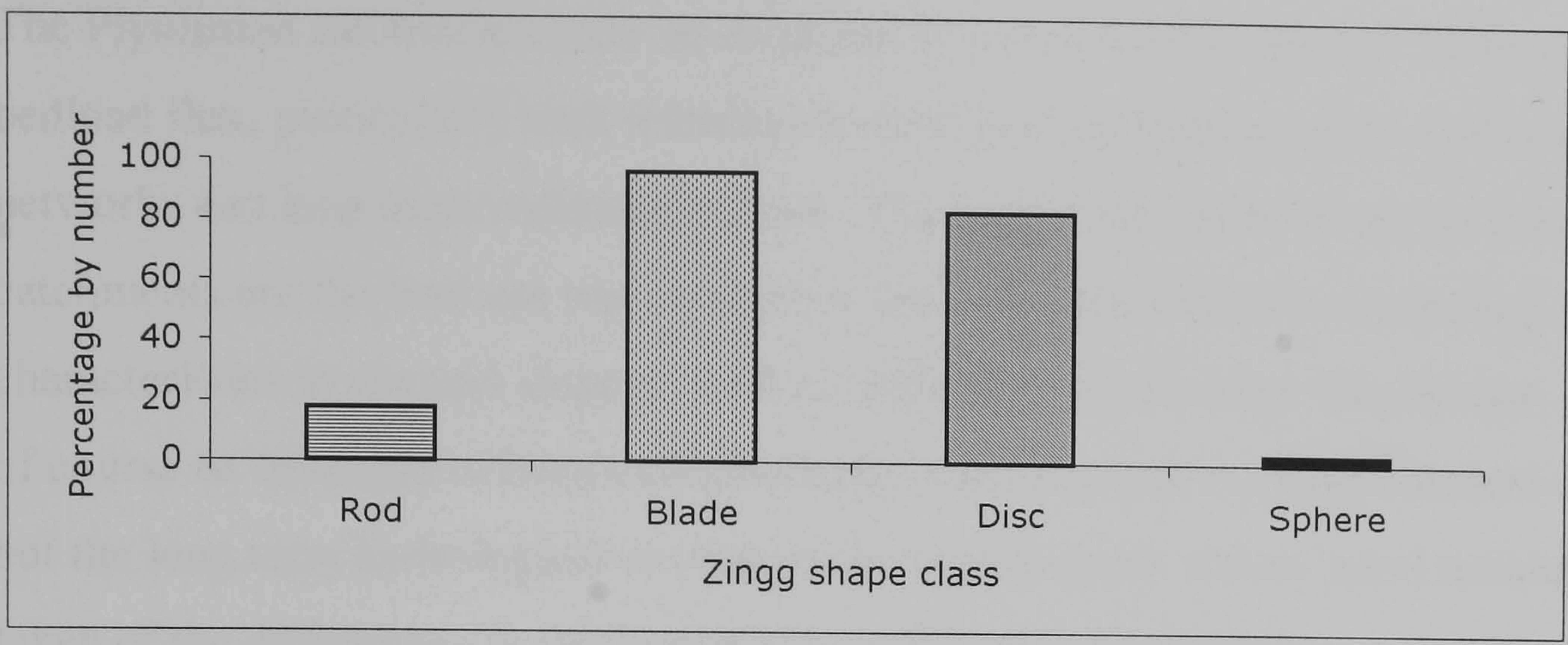


Figure 1.9. Particle shape distribution of the Nant Tanllwyth and Afon Cyff.

Shape distribution was also examined based on Krumbein. The distribution of bedload is shown below and demonstrates the dominance of sphericities of between 0.4 and 0.6.

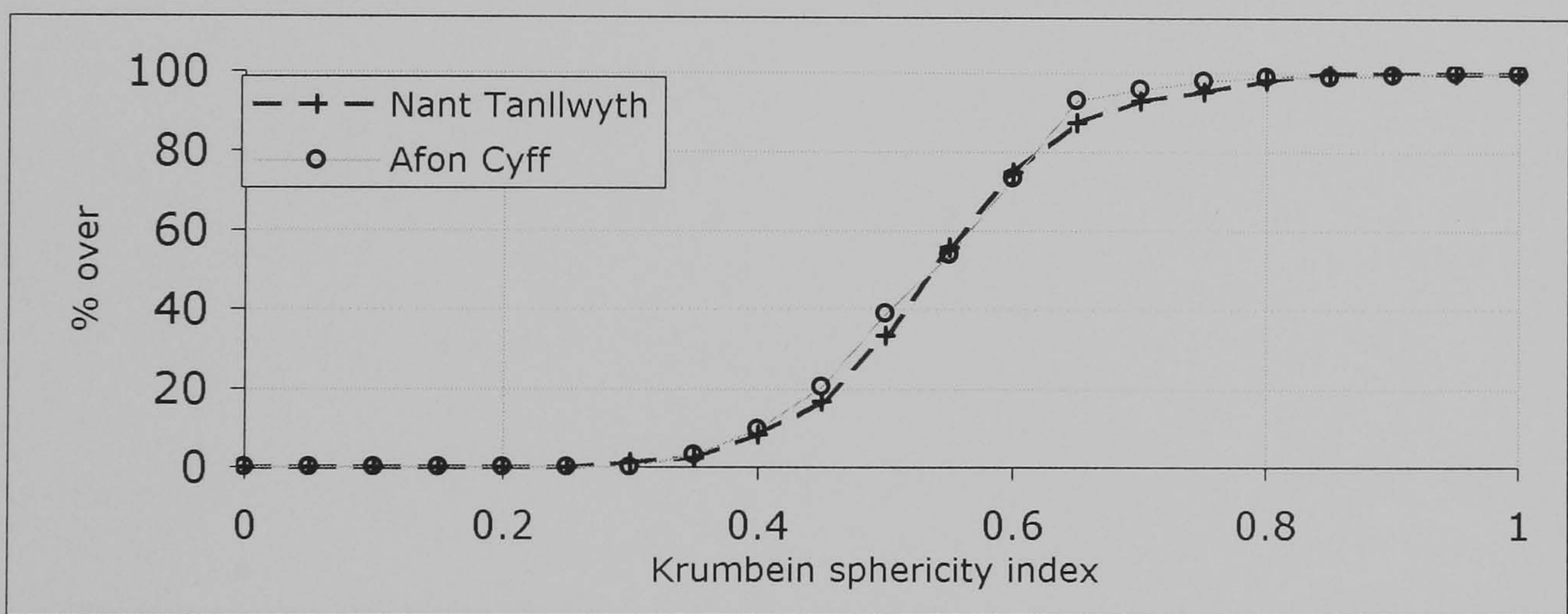


Figure 1.10. Krumbein sphericity index of both channels

1.6. Summary

The impacts of new forest guidelines for timber harvesting in the United Kingdom need to be examined for their effectiveness. The Plynlimon catchments satisfy the scientific and logistical needs of a location to study these impacts. This is especially important with regard to access to sites and knowledge of the timing of forest operations.

The Plynlimon catchments offer an excellent resource for the study of forest practice on bedload flux, particularly with reference to their proven hydrological monitoring networks and long term sediment records. The only major differences between the catchments are the land use and catchment area, with the channels exhibiting similar characteristics in channel slope as well as bedload size and shape distribution. It would of course be desirable to have two identically sized catchments with different land uses, but the long term hydrological records of the two channels allows good account to be taken of the differences in catchment area and stream discharge.

Section 2: Previous Literature

This section will address the pertinent literature on coarse sediment transport and the use of bedload tracers. In addition, the role of plantation forestry in modifying coarse sediment flux and its impact on the ecology and geomorphology of fluvial systems will be considered.

The literature can be subdivided by geographic region and by the nature of the sediment involved. Examples will be drawn from upland areas and will concentrate on bedload, as opposed to suspended sediment. To understand the effects of afforestation on sediment transport, it is first necessary to examine the mechanisms by which sediment is transported through the fluvial system. Part one of this literature review will deal, therefore, with aspects of flow competence, dynamics of sediment transport, volumes transported and movement of individual grains and clast clusters, as well as an examination of the techniques used for their study.

Part two will examine the effects forestry has had on the supply of coarse sediment to river systems and the subsequent effect on fluvial bedforms. It will deal specifically with the effects of the felling stage of the forest rotation on bedload transport. Part three will briefly examine how fluxes of coarse sediment through a channel affect bedform assemblages.

2.1. Coarse sediment dynamics

Several approaches can be taken to define what constitutes bedload. Gomez (1991) stated that bedload is the proportion of the matrix that moves by saltation or rolling. This approach, whilst simplifying bedload in a given flood event for a given channel, does not define a size bracket for those particles defined to be bedload or suspended sediments. Leeder (1983) assumes anything under 0.2 mm goes directly into suspension, whilst recognising that one clast size may under some conditions be entrained in the flow while at other times may be moved by rolling or saltation. Moore and Newson (1986), working in the Plynlimon catchments, used the total volume of sediment held within given bedload traps to define bedload which included any material collected from stilling ponds where sediment could settle.

The dispersion and transport of sediment in alluvial channels is the result of transport of individual grains (Parker, 1990; Church and Hassan, 1992). In most natural gravel bed rivers, bed material is immobile in ordinary flow conditions and moves only during floods (Ferguson, 1994). Understanding some of the physical principles of transport will be essential before undertaking an empirical study and attempting to draw any realistic conclusions from the methods used in this thesis.

This section will examine the mechanisms needed to entrain particles, initial motion criteria, the way in which particles are transported and will discuss the effects of size and shape on the probability of entrainment and transport. Once entrained, the nature of how sediment is transported is critical to investigating the impacts of clearfelling on sediment dynamics. Any forestry induced changes on the parameters governing transport itself will subsequently feed back to total transport rates within the channel (Powell, 1998).

2.1.1. The mechanisms of transport

The flux of coarse, fluvial sediment can be subdivided into its constituent parts and associated mechanisms: entrainment (the point of initial motion of the clast), transport (the time in which the clast is in motion), and deposition and subsequent imbrication (the point at which transport ceases and the clast stops). Presenting these constituent parts separately creates a significant challenge as any one component of the transport process is not discrete.

Various studies have examined initial motion criteria and the shear stresses and mechanisms required to entrain particles on a gravel river's bed (Brayshaw *et al.,* 1983; Reid *et al.,* 1984; 1992; Andrews and Smith, 1992; Bridge and Bennet, 1992; Ferguson, 1994; Carling *et al.,* 1998). The point at which an individual particle is entrained and set in motion can be defined by the dimensionless shear stress τ^*_c. Shields (1936) defined a critical shear stress τ^*_c of incipient motion, and concluded that no transport below τ^*_c of 0.06 would occur.

Andrews and Smith (1992) examined marginal movements and calculated that occasional entrainment starts with dimensionless shear stresses of around 0.02 and continue to 0.06. Given time at these marginal stresses, a high proportion of bed material will become mobilised. These authors highlight the importance of particle shape and packing (imbrication) in determining the actual numbers of particles in motion. Ashworth and Ferguson (1989) also report this and concluded that threshold shear stress is more dependent on the *relative* rather than the *absolute* grain size of an individual particle. Baker and Ritter (1975) noted that in shallow streams, or during low flows, entrainment is higher than expected by empirical prediction. Lift forces are shown to be higher in shallow streams, as opposed to during high flows where lift forces are reduced in deep water areas.

In Squaw Creek, Montana, a steep stream with transport undertaken exclusively by snowmelt, Bunte (1992) reported the strong effects of hiding of individual clasts on total transport volumes and argues that coarse material transport is poorly related to discharge. The build up of sediment shoals and movement of slugs might also control the pattern and distribution of sediment movement (Warburton and Davies, 1994; Nicholas, *et al.*, 1995; Wathen and Hoey, 1998). Consideration of this aspect of transport is included in the discussion.

In the discussion of Andrew and Smith (1992), Reid criticises the work for ignoring the real importance of interlock between particles (Brayshaw *et al.,* 1983; Reid *et al.,* 1984). He suggests that values of τ^*_c are difficult to define as consolidation leading to a wide range of entrainment thresholds. Brayshaw *et al.* (1983) found that with interlocked particles, 46% were entrained in a flow, whilst 87% of particles on an open plane bed were entrained. Thus, the influence of clusters is a major determinant on sediment sorting which is also highlighted by Reid *et al.* (1984). Due to the difficulty of characterising hiding and pebble clusters, Armanini (1992) ascertains that it is impossible to attribute *any* values to hiding mechanisms and armouring processes

(Parker and Sutherland, 1990; Gomez, 1994). Armanini (1992) further argues that any true representation of entrainment values is also impossible.

The nature of deposition and subsequent imbrication is crucial to total flux, as it governs the probability of further entrainment and transport. It relates directly to the clustering probabilities studied in particular by Reid and co-workers during the 1980s (Brayshaw *et al.*, 1983; Frostick *et al.*, 1984; Reid *et al.*, 1984). Paola and Seal (1995) demonstrated strong selective deposition, even in cases where equal mobility of entrainment was exactly satisfied, this established grain size patches in different channel patterns. Gomez (1994) showed the importance of selective transport to fluvial landforms; specifically how feedback loops constructed new flow structures and subsequently affected future bed dynamics.

2.1.2. The probability of transport

The dispersion of river gravels of different size and shape and at different stages of the transport process has resulted in a number of contrasting conclusions with regard to the probability of transport. These can often be attributed to local hydrological and geomorphological regimes. Gomez and Church (1989) maintain that there is no universal equation for bedload transfer due to these factors. Arkell (1985) concludes that the data derived from the several Plynlimon headwater steams "clearly question the assumptions made in the application of most sediment transport formulae". No relationship was found with tractive forces, but the importance of sediment stores and shoals was noted (including the influence of man made structures, including bridge struts). Arkell highlights that the development of these formulae from specific circumstances (often flumes) normally rule out any universal application. This section will consider the importance of size, shape and packing of bed material in governing the probability and distribution of bedload transport at the Plynlimon catchments.

PARTICLE SIZE

The question as to whether a particle's size affects its probability of entrainment and ultimately therefore influences its final transport distance, is one of the key questions continuing to drive research on coarse sediment transport in gravel bed rivers. Is the effect of hiding and protrusion strong enough to cancel out the effects of mass and make all particles equally mobile (Ashworth and Ferguson, 1989)? Evidence is available to suggest that gravel bed rivers exhibit both equal mobility and selective transport in different regional, channel and flow conditions. The differing opinions on the effect of size can be summarised as the theories of *equal mobility* and *size selective transport.* Equal mobility (Parker *et al.,* 1982; Church *et al.,* 1991; Komar and Shih, 1992) is where all of the size distribution is assumed to move at the same long term velocity. Size selective transport (Reid *et al.,* 1992; Ferguson *et al.,* 1996) occurs when individual grain sizes are preferentially transported according to clast size. Size selectivity may take place at either end of the grain size distribution.

Early discussion argued specifically towards one theory. For example, Einstein (1950) argued that the average step length of a clast would be 100 times particle b-axis. Parker *et al.* (1982) working on Oak Creek concluded that once the pavement is broken, all sizes are equally mobile. Parker *et al.* (1982) recognised equal mobility to be a first order approximation, as re-examination of the data suggested a coarser bedload flux for high flow events and slight change of bedload size distribution with shear stress. Lower flows favour smaller bedload sizes, whilst higher flows favour a larger bedload grain size distribution. Once shear stress exceeds a certain value, bedload approaches a state of being equally mobile. Using the White River, Lyngsdalselva, Feshie and Dubhaig rivers to examine sediment transport relationships and size distributions, Ashworth and Ferguson (1989) found size selectivity at all but the highest flows and shear stresses. However, a state approaching equal mobility was demonstrated at these highest discharges. Ashworth *et al.* (1992) showed that despite daily variance in shear stress and total transport, the D_{50} remained stable, and both load *and* deposition were finer than the bed, indicating selective transport. Working in experimental flumes, Kuhnle and Southard (1988) found that after test runs the remaining bed surface was coarser in all but the highest flow experiments which showed selective transport of smaller clasts.

Field observations do not entirely explain downstream fining by abrasion in stream and lead to the conclusion that at a range of flow levels, selective transport will predominate. However, in high flows and during the breakdown of armour (Moog and Whiting, 1998) equal mobility will be approached. These conditions will also occur in areas of low bed stability (Kuhnle, 1992) and perhaps in flashy, desert, ephemeral rivers, such as the Nahal Hebron (Hassan *et al.* 1984; Reid *et al.* 1998). Kuhnle (1993) examined transport of bimodal sediment distributions and showed transport to approach equal mobility at high flows, but remained strongly size selective at low flows.

Sediment transport distance has also been shown to be dependent on relative, rather than absolute grain size. Larger particles in an individual matrix will protrude more than smaller particles and have a higher chance of entrainment (Fenton and Abbott 1977; Ashworth and Ferguson, 1989). Several tracer experiments have recognised this; for example Church and Hassan (1992) scaled tracer sizes to the median bed size. The conclusion was that larger clasts showed a decline in mobility where $D_i/D_{50sub} = 10$. Within smaller size ranges, less relation was shown to mean bed size, concluding that the trapping of small clasts in cavities within the bed affects overall travel distance. Powell (1998) states that bedload grain size distributions are modified as different size fractions are routed along different transport pathways, leading eventually to selective transport. Shih and Komar (1990) state:

The movement of grains in a mixture is affected by other particles, since small grains can be sheltered by the larger, and the largest particles have greater exposure to flow. As a result, each size fraction will have its individual transport rate which depends on the total distribution of sizes available for transport.

There is no clear consensus on equal mobility or selective transport in gravel bed rivers. Equal mobility has to be a first order approximation for sediment budgets (Parker *et al.*, 1982) though selective transport has been shown to be relevant at a range of discharges (Ashworth and Ferguson 1989). Complex models (Armanini, 1992) have attempted to address the issue numerically, but still omit factors accounting for hiding, protrusion and armouring which are proven to be critical. Billi (1986) visually assessed pebble clusters within the Nant Tanllwyth and Afon Cyff and showed a significantly greater number of pebble clusters in the Afon Cyff. Although the work does not analyse the relationship of these clusters to sediment transport loads, the importance of these clusters in limiting the initiation of transport is highlighted. A greater stress is required to entrain a similar size range of all clustered particles and hence makes equal mobility of particles likely at the break up point of the clusters.

PARTICLE SHAPE

Determining the effect of particle shape on sediment transport has mainly relied upon the use of tracers, as abrasion processes change particle shape and distribution downstream (Huddart, 1994). Carling *et al.* (1992) found that shape affected initial motion criteria on a variety of bed roughnesses. They examined initial motion criteria for set shapes on three beds and concluded that shape and orientation of a clast was as important as its mass in controlling its likely entrainment. Carling *et al.* (1992) also argue that the complexities of shape and size distribution, as well as particle packing mean a mechanistic approach to modelling sediment movement is required. The effect of particle shape on bedload transport has also been examined by Schmidt and Ergenzinger (1992); Gomez (1994); Huddart (1994) and Warburton and Demir (in press) and despite some disparity, a general pattern for the travel distance of different shapes emerges. A major problem has been removing the effects of particle size, which have proven difficult to separate out from those of shape (particularly relevant in terms of shape and packing).

Working in the Allt Dubhaig, Scotland, Ferguson and Wathen (1998) found that shape has a secondary (after size) role in determining travel distance, with 90% of variance in travel distance explained by relative grain size and Shields stress. Gomez (1994) found the mobility of flat fine gravels is enhanced by the lower surface roughness of the associated armour, with ellipsoids travelling the least distance. Although angular gravels are restricted in their mobility by interlocking effects, this is offset by their projection into the flow and greater overall mobility. Also highlighted is the importance of the shape of gravel in the armouring process, with flat gravels constructing stronger armour layers. Bedload output from streams with flat gravels is likely to be lower than from streams with spherical gravel matrices. Schmidt and Ergenzinger (1992), working in the Lainbach River, Germany, recommended separate distributions for particle shapes, finding elongated rods to have the greatest transport distance and discs remaining close to the seeded starting point. Stott and Sawyer (in press) showed that the highest mean travel rates were for rods and spheres, which are the two most under represented groups in the particle shape distribution of the Nant Tanllwyth and Afon Cyff. Further evidence of this pattern of selectivity is presented in Gintz and Schmidt (1991) with a sequence of rod, ellipsoid, ball and plate travelling decreasing step lengths. Brayshaw *et al.* (1983) examined the wider implications of interlocking of differing shapes and found the combination of lift and drag, and therefore entrainment probability, was governed by particle exposure. Given the conclusions of Gomez (1994) above, the shape of particles in differing streams is important, though in most cases secondary to size. We might therefore reasonably expect streams having different flow regimes on different geology and a different proportion of clasts in the same shape category to exhibit marginally different bedload transport regimes (Komar and Carling, 1991).

ARMOUR AND PAVEMENT

The threshold for entraining river gravels can change through time due to the armouring and pavement process. Pavement is a coarse surface layer maintained by successive periods of bedload transport during which all bed material sizes move (Parker and Klingeman, 1982). Parker *et al.* (1982) argued that in gravel beds with pavement phenomena, all size ranges are transported equally. Milhouse and Klingeman (1973) found bedload transport per unit discharge increased after peak flow. This they attributed to the shift in critical discharge after the destruction of the bed armour. In contrast Nanson (1974) working on Bridge Creek, Saskatchewan River, observed bedload per unit water discharge to be greater prior to the spring flood. This was irrespective of whether samples were taken from rising or falling limbs: critical discharge required to entrain bedload increased after the flood peak.

Gomez (1994) says that the throughput of fine sediment load through a system may mask the effects of hiding, which would be particularly relevant in periods of lower flows. Carling (1989), considering bed load transport as a function of excess stream power, found winnowing of smaller particles occurring from a largely undisturbed framework, which at low shear stresses made transport strongly supply limited. However, when the framework or armour is disturbed and the sub-armour is exposed, a new threshold of transport is revealed, demonstrating the importance of armour to the coarse sediment budgets (Parker and Klingeman, 1982).

SUPPLY CONSIDERATIONS.

Static armour layers have been shown to form under conditions of no inputs of sediment from upstream (Sutherland, 1987) and thus adjustment of bedload supply properties may affect the armouring process in any channel.

Newson (1980b), using bulk bedload traps and comparing sediment outputs with flood magnitudes, found evidence for phases of both supply-limited and transport-limited bedload output. In the same Plynlimon catchments, Moore and Newson (1986) found both experimental catchments were supply-limited, evidenced by high flows not always according with high bedload outputs. It is often difficult to disentangle these data from the effects of previous events with regard to bed armouring and pavement formation.

Bennet and Bridge (1995), examining the controls of bedload transport in laboratory conditions, induced aggradation and examined the reaction on total transport rate. Flumes were systematically adjusted by tilting and changing the sediment availability to the flow. Increasing sediment supply (sediment overloading) resulted in increased imbrication of pebbles, a decrease in mean water surface slope and reduction in total bedload transport. Conversely, reduction in sediment inputs resulted in rapid downstream erosion and upstream deposition.

Working in the Plynlimon catchments, Billi (1986) highlights a number of controlling parameters that may govern sediment transport patterns. Billi particularly studied the co-existence of individual particles with one another and classified these in terms of interlocking, imbrication, bed armouring and the bedforms of pebble clusters and transverse ribs. In addition, the examination of the channel morphology of the Plynlimon catchments showed that stepped pools were common in both channels (17 in each) along with boulder steps (72 and 110 in the Nant Tanllwyth and Afon Cyff respectively).

2.1.3. Coarse sediment tracing

HISTORICAL DEVELOPMENT

Tracers in geomorphology provide an opportunity in a variety of disciplines to study processes in action, and tracers have been widely used in fluvial geomorphology. Chemical, radioactive, and physical tagging of material can elucidate information not readily available using surveys involving measuring mass deposits or fluxes alone. First attempted by Leopold *et al.* (1964) and Takayama (1965) tracers were essentially simple painted clasts which were seeded and tracked during their progress downstream. Their use was continued by Thorne and Lewin (1979). However, the painted pebble method gave poor recovery rates (less than 50%) and elucidated data only from the exposed section of the matrix (Church and Hassan, 1992). Significant improvements to the technique were made by Hassan *et al.* (1984) by introducing a magnetic core into natural tracers to increase recovery rates. This technique was also used by Reid *et al.* (1984). Ergenzinger (1985) outlined a variety of implanted core techniques and analysed improving recovery rates. Developments in technology and experiments using magnetically tagged clasts have allowed particles to be monitored during the passage of a flood event (Schmidt and Ergenzinger, 1992). Using active, rather than passive tracers, this allowed positive identification of clasts without removal from the bed, and furthermore, tracers could be located from deep and imbricated positions (Schmidt and Ergenzinger, 1992; Ferguson *et al.,* 1996). Large-scale tracing experiments have not yet used this system, but have utilised the implanted magnet approach (Ferguson and Wathen, 1998). Alternative tracer techniques have also been applied in fluvial geomorphology. Radioactively tagged sediments were used in the 1960s (Hubbell and Sayre, 1964) and more recently by Bonnet *et al.* (1989) in the Plynlimon catchments. Also working in the Plynlimon catchments, Arkell *et al.* (1983) used baked clasts to artificially increase magnetism to aid location. This method has recently been used in the Afon Trannon to estimate total bedload flux (Mount, pers comm). The purpose of the development of tracers as a tool in coarse sediment transport in fluvial geomorphology is to examine transport in as near natural conditions as possible (Ergenzinger *et al.,* 1989). It also allows examination of movements in the entire system, rather than just studying the total mass of sediments with a channel, for example by using bedload traps (Newson, 1980a).

PASSIVE TRACING SYSTEMS

Tracers can currently be divided into passive and active, though this section will concentrate specifically on passive tracing methods. Passive tracers are placed in a channel and can be differentiated by their construction. They may either be constructed from artificial material (Gintz and Schmidt, 1991; Brewer *et al.,* 1992), or natural bed material (Ferguson and Wathen, 1998). Tracers can also be defined by their method of location, marked using paint (Takayama, 1965), artificial magnet (Ferguson and Wathen, 1998) or baked for total magnetism (Arkell *et al.,* 1983). They are either then located at fixed intervals (for example monthly), or more usefully on an event basis, after a sediment mobilisation threshold or other arbitrary flow threshold. Low recovery rates for passive tracers, (e.g. 15% after 20 floods by Thorne and Lewin (1979)) led to the development of passive tracers that could be detected at depth. These tracers, implanted with either a ferrous material (Reid *et al.*, 1984), or a magnet (Hassan *et al.*, 1991; Ferguson *et al.,* 1996) allow for a representative number of clasts to be tagged in a channel at a reasonable cost. This allows repeated visits over a large area which was not possible using the coil monitoring technique (Reid *et al.,* 1984). The ability to monitor a large dataset and to understand the *distribution* of steps and rest periods is essential to an understanding of the overall dynamics of sediment transport (Einstein, 1937).

Schmidt and Ergenzinger (1992) further highlight that the techniques allow the determination of the cumulative travel lengths covered by clasts, with details on step lengths, duration of rest periods and pathways of individual particles. Natural cobbles tagged with iron implants were traced in the Lainbach River, Germany, which could be later detected with a locating device. Tracers ranged from 330 g to 5020 g, and had flatness indices ranging between 107 to 380. Recovery rates ranged form 92% after the first event to just 17% after the eighth flood. Losses were explained both by clasts leaving the 1 km study reach, or by burial so deep as to prevent recovery. Results showed some tendency for selective transport, but this was masked by the fact that the starting position and shape of clasts were not controlled. Church and Hassan (1992), reviewing several coarse tracing experiments, found that clasts larger than the median of surface material showed a steep decline in mobility.

The following section will deal with a variety of results yielded from tracing experiments, concentrating on those in upland rivers and from the large bedload size fraction. Although tracers have also been used in conjunction with flumes (Bagnold, 1980) the most important clast tracing technique for studying changes by forest operations on coarse sediment transport, is within natural channels. Dietrich *et al.* (1982) discusses the pre-requisites for tracer study which include a requirement of 100 per cent recovery rates, an achievement that no study published to date has attained. The reason for this requirement is that immediately recovery rates drop below the 100% level, uncertainty over the reason for tracer loss exists. The uncertainty is centred around why specific tracers are lost, with mean values incorrectly calculated as it is not clear if tracers were lost due to deep burial or because of transport 500 m through the channel reach. This error however seems inevitable to continue, as the physical methods of tracing and trapping sediment do not allow for perfect relocation. Hassan and Church (1992) show that distributions of distances moved of tracers are highly stochastic, most plots of distance versus particle size showing little correlation. Schmidt and Ergenzinger (1992) observed that particle velocities tend to be randomly distributed as overall velocity is controlled by rest periods, which themselves are random. Laronne and Duncan (1992) noted the importance of deposition location on bedforms, for the subsequent entrainment of tracers. Tracers on bedforms exposed and less frequently submerged in flow had a lower probability of being entrained. Thorne and Lewin (1979) also used tracer pebbles to establish a relationship between previous bedform and the next downstream.

The importance of vertical exchange of clasts within a bed has been illustrated by Frostick *et al.* (1984) where fine material was shown to permeate through the bed structure. Hassan (1990) attempted correlation between burial depth and travel distance, and defined several discrete particle burial mechanisms. In general, less tracer activity was associated with deeper burial. This conflicts with Drew (1992) who observed preferential scouring and no association between burial depth and tracer movement.

2.1.4. Abrasion

Downstream fining and rounding of coarse river sediments is well documented (McPherson, 1971; Mills, 1979; Knighton, 1980; Huddart, 1994; Ferguson *et al.*, 1996) and these changes in the sediment characteristics are commonly explained in terms of selective entrainment, transport, and deposition (hydraulic sorting), or the physical modification of clasts by mechanical abrasion. Such abrasion processes have been studied in the past using abrasion tanks (Kuenen, 1956; Bradley, 1970; Bradley *et al.*, 1972) and tumbling barrels (Daubree, 1879; Wentworth, 1919; Marshall, 1927; Bigelow, 1984). Under the laboratory conditions used by these workers, clast weight losses per unit distance were consistently lower than downstream reductions in weight loss derived from field sampling (Bradley, 1970; Schumm and Stevens, 1973; Adams, 1978, 1979). The observed difference between laboratory simulated and field measured reduction rates have been attributed to either weathering (Bradley, 1970), hydraulic sorting processes (Mackin, 1963) or the theory of 'abrasion in place' (Schumm and Stevens, 1973) whereby clasts may be abraded by vibration within the bed without net downstream movement. Laboratory simulation of this vibration yielded promising results (Schumm and Stevens, 1973), though the authors did not report significant abrasion occurring in their experiments. Brewer *et al.* (1992) used 25 mm rock cubes, shown using extensive laboratory simulation of abrasion processes to exhibit similar weight loss patterns and rates to natural channel material (Brewer, 1991), to monitor abrasion. The cuboid tracers, which were sawn from large pieces of parent bedrock, were bolted or tethered with string to the channel bedrock. The standard size cube eliminated differences in surface area between tracers, and allowed easy identification of impact marks or loss of corners and edges. Weight losses sustained by 39 tracers over a six week period in a coarse upland channel indicated the potential of 'sandblasting' as an additional 'abrasion in place' process.

2.2. The effects of forestry

Introduction

The impact of afforestation on the landscape of the British uplands can be borne out in terms of statistics. Forestry has been the largest single land use change in Britain, and in the 1970s new planting took place at a rate of about 40 000 ha yr^{-1} (Robinson and Blyth, 1982). Further, it is the cultivation of non-indigenous, fast growing species such as Sitka Spruce (*Picea sitchensis)* shows the most significant change (Clarke and McCulloch, 1979). With forest stands attaining maturity after c. 40 years and the peak of forest planting not reached until after the 1950s, only a small proportion of timber planted has been harvested (Stott, 1997a).

Britain is within a period where commercial plantation forest operations in the 'harvest stage' of the forest rotation are reaching a peak. Examination of the harvest stage and its effects on fluvial systems is particularly important. However, the impacts of timber harvesting on hydrology and fluvial geomorphology in a British context are still poorly understood (Binns, 1986). This section intends to provide an overview of the effects of forestry land use on stream networks in upland catchments and on downstream fluvial geomorphology. The section will examine effects on three areas: hydrology, suspended sediments and bedload. It will address the different stages of the forest rotation, but will concentrate and review the major effects that forest clearance operations have had on sediment movement in upland streams. The Binns (1979) framework of ditching, planting, pole and harvesting will be used throughout the text.

Forest planting procedures in the British uplands are to first plough furrows in the moorland on which the trees will be planted. This is followed by the construction of a drainage network to remove excess water. Thirdly, trees are planted in the drained soil. A description of the guidelines is given in (Taylor, 1970) and Thomson (1979). Taylor states in his conclusions that "...land need no longer dictate what he [*the forester*] should grow, or determine the rate of growth he should accept". Forest practice in the U.K has been to fit plantation forest into areas otherwise too marginal for alternative land use. Management guidelines from the Forestry Commission (Mills, 1980) recognises the problem of sediment adjustment in clearfelling and thinning and does recommend felling strategies to limit brashings and lops falling into stream channels.

Areas of forest clearance and logging activity are associated with the use of heavy machinery and major land use change (Stott, 1987) and felling procedure has typically taken place using cable crane and skyline timber extraction in the U.K. Fredrikson (1970) showed that different forest logging practices (in the Pacific Northwest, USA) could reduce sediment outputs from the fluvial system, with clear cut basins have significantly higher sediment yields than patch cut basins, with aerial cable "skyline" removal techniques.

2.2.1. Forestry effects on hydrology

With the travel distances of unrestrained clasts and the discharge of suspended sediment directly related to discharge parameters, significant importance must be attached to changes in upland hydrology caused by any stage in the forest rotation cycle.

Before the 1950s, it was assumed that the propagation of plantation forestry led to greater water yields in water supply catchments (Cuthbertson, 1948) and forestry was often seen as a positive step in protecting reservoir supplies. It was Law (1956) who undertook the first serious study on the effects of forest land use on water yield in the catchment of Stock's Reservoir in Lancashire. Using a natural lysimeter planted with mature Sitka spruce, Law's experiment concluded that the forest canopy used significant water through transpiration and subsequently lowered water yields from afforested catchments, evaporating 275mm km^{-2} more than an equivalent grassland catchment. He translated these water losses into financial terms, claiming that the foresters owed the water resource managers some £550 per ha of trees planted.

The impact of forestry on upland hydrology is also governed by the position of the forest in the commercial forest cycle. During the establishment phase, drainage ditches (see Plate 3.1.) may promote the rapid runoff of water, and decrease time to flood peak. On the 152 ha Coalburn catchment in Southern Scotland, establishment of drainage ditches meant that time to flood peak was reduced by 50 per cent (Robinson, 1980; Robinson and Blythe, 1982).

Plate 3.1. Drainage ditches in Nant Tanllwyth catchment.

During growth and maturity, infilling of drainage ditches with needles and other vegetation will reduce the impact on flood timing (Leeks and Roberts, 1987). Blackie and Newson (1986) suggest that timing and magnitude of flood peaks would be reduced due to forest canopy interception as the canopy begins to close. At Balquhidder, in Scotland, it was found that the duration and magnitude of small and medium sized flood peaks was lower in the afforested Kirkton catchment, than in the adjacent paired Monachyle moorland catchment (Johnson, 1991). There are physical reasons why water yield will reduce. These include turbulence (Clarke and McCulloch, 1979), total interception (Calder, 1986), advection from the canopy (Newson and Calder, 1980) and evapotranspiration (Binns, 1979). Both Clarke and McCulloch (1979) and Johnson (1990) show how losses from upland catchments with high precipitation are likely to be proportionally greater than from catchments with low precipitation. This is due to higher precipitation intensities and stronger winds which help to ventilate the canopy.

The effect of harvesting has been to cause a dramatic increase in water yield after forest operations. As a part re-examination of the work of Hibbert (1967), Bosch and Hewlett (1982) examined the effects of removal of canopy in 94 catchment experiments and showed a linear relationships between increase in water yield and removal of forest cover. Removal of coniferous vegetation was found to have the greatest effect on increased streamflow (Rothacher, 1970; Harris, 1973). The authors concluded that the reduction of forest cover by 20 percent or less was unlikely to be detected as changes in flow parameters. The majority of these case studies were in the USA and involved the clearfelling of natural forests, but the physical reasons for the changes are, it may be argued, relevant also to plantation forests in upland Britain. Johnson (1990) determined interception losses for the Balquhidder catchments in central Scotland and showed largest interception losses of water in the summer months, reaching 79 % in May 1985. He also showed how the shape of the tree and the age of stand (relating to distance from the stem) had an effect on losses, with throughfall increasing and stemflow decreasing with increased age of forest stands.

2.2.2. Forestry effects on suspended sediment yields

Afforestation in upland Britain traditionally uses damaging furrow drainage to drain the surface peat for planting (Stott, 1997a) and these drains allowing rapid removal of both water and sediment into main river channels. Some of the largest demonstrated effects of afforestation have been manifested in changes in suspended sediment outputs.

Working in the Coalburn catchment, Southern Scotland, Robinson and Blythe (1982) studied sediment outputs before forestry, during drainage operations and during early growth stages. Sediment yields were shown to dramatically increase during and in the five years after drainage. Suspended sediment yields were 3 t km^2 yr^{-1} in the moorland area before ploughing and ditching and rose to 25 t km^2 yr^{-1} during the three month ploughing period. Yields declined to 13 t km^2 yr^{-1}during the first four years of growth. In the Balquhidder catchments, Johnson (1993) found that suspended sediment yields increased by up to 818% due to forest operations in the Kirkton catchments, attributing both forestry and changed precipitation patterns as factors influencing the increase.

Polarised reviews [Authors opinion] of the effects of upland forestry on soil erosion and subsequent sediment outputs have been undertaken by Moffat (1988) for the *Forestry Commission* and by Soutar (1989) for the *Nature Conservancy Council.* Moffat (1988) argues that at Balquhidder, most sediment comes from first-order watercourses in the upper sections of the catchment (above forested areas in these studies) and that afforestation is not responsible for increase in sediment yields. Moffat (1988) adds that few studies into the effect of harvesting operations have been undertaken in the UK. Those that have (for example Lewis and Neustein (1971)) show that selective harvesting techniques can protect exposed soil from erosion and that erosion intensity was 'insufficient to justify managerial concern'. Moffat also refutes evidence from other regions in the world that suggest increased landslides after forest operations (Pritchett and Fischer, 1987). Although acknowledging the lack of published evidence on the effects of harvesting, Soutar (1989) highlights it as a major cause of erosion worldwide. Ursic (1991) examined the effects of two different felling mechanisms on hydrology and sediment outputs on stands of shortleaf pine (*Pinus echintata*). Concentrations of sediment were found to be 40 per cent lower in the skidded catchment than in the control in the first year, but exceeded the control catchment in the following years, implying delayed transport. Recommendations and conclusions from this study suggested that even careful logging strategies would result in increased sedimentation in logged catchments, whilst maintaining recommendations that headwater channels are exceptionally vulnerable and require care in harvest. With harvesting techniques changing due both to new technology and environmental concerns, it is appropriate to examine the differences in harvesting techniques and the effects on bedload transfer.

2.2.3. Forestry effects on bedload yields

The effects of forest operations on bedload transport in gravel bed rivers has received relatively little attention, despite its impacts on fish habitats, downstream morphology and implications for water resources. This is especially true of harvesting in a United Kingdom context (Maitland *et al.,* 1990). Records of both increases and reductions in bedload outputs have been demonstrated in the presence of afforestation, though at different points within the forest rotation, as highlighted by Leeks (1992).

The impacts of forest operations on bedload transport are split into the stages of the forest rotation. Much of the literature discussed highlights the statistical relationships between yields, land use and flooding. While some highlight the importance of a process based approach (Moore and Newson, 1986), few address the problem with experimental studies. It is again difficult to disentangle the relationship between the hydrological effects discussed in section 2.2.1 (which themselves effect sediment movement) and the effects of the forestry on sediment output.

Leeks and Roberts (1987) examined the impact of ground preparation and planting in the Llanbrynmair catchments, mid-Wales. They found that this caused a change in both total output of bedload and its size distribution. This was mostly attributable to the loose gravel from road construction in the preparation stages. No evidence for significant reduction in outputs after the initial drainage was noticed, with high yields continuing through erosion of active sediment sources. The size distribution of bedload from the forested Cwm catchment became finer during the planting period. This sedimentation has potentially serious implications on downstream fisheries.

In the Mature forest stage, studies suggest that yields of bedload still maintain the high output levels seen during planting and ditching. Newson (1980a) and Kirby *et al.* (1991) studying the Afon Cyff and Nant Tanllwyth catchments on Plynlimon, found that the main sediment source was the drainage ditches. These ditches are set in a herringbone pattern around the natural drainage channels, and provide significant sediment sources. Bedload outputs were shown to increase quickly immediately after forestry operations commenced, and to remain at a high level during the early growth stage. Newson (1980a) suggests that it is during the greatest floods that bedload output is most increased under the maturely forested Tanllwyth catchment (planted in 1949/50) and that this suggests new sediment sources to explain this increase.

The felling stage has received relatively little attention in UK catchments, despite significant research in the USA (Swanson and Swanson, 1976), New Zealand (O' Loughlin *et al.,* 1978) and Asia (Froelich and Starkel, 1993). Some work has again been undertaken at the Plynlimon catchments, with a network of sediment traps monitoring bedload yield before and after clearfelling in the Hore, a sub-catchment of the River Severn. Leeks and Roberts (1987) found an increase in bedload outputs from 1.2 $m^3 km^{-2} yr^{-1}$ to 23.4 $m^3 km^{-2} yr^{-1}$ in a tributary of the Hore catchment on Plynlimon, mid-Wales during removal of trees using skidding techniques, though after tree build up in ditches, yields decreased. The initial impacts of clearfelling can cause a *reduction* in bedload outputs attributed to build up of bedload behind debris jams, but as these jams decayed, yields rose to more than five times their original level (Leeks, 1992). A strategy of staggering the clearfelling period to reduce the bedload pulses both from immediate machinery and breakdowns of dead organic matter was suggested. The timing of felling is also noted, with late spring (in an upland British context) seen as the most appropriate time to avoid damage by winter floods and allow consolidation and re-vegetation during the spring and summer. A useful model is attempted by Leeks (1992) of sediment production (both bedload and suspended sediment) based on the first and second rotation of forestry (see Figure 2.1).

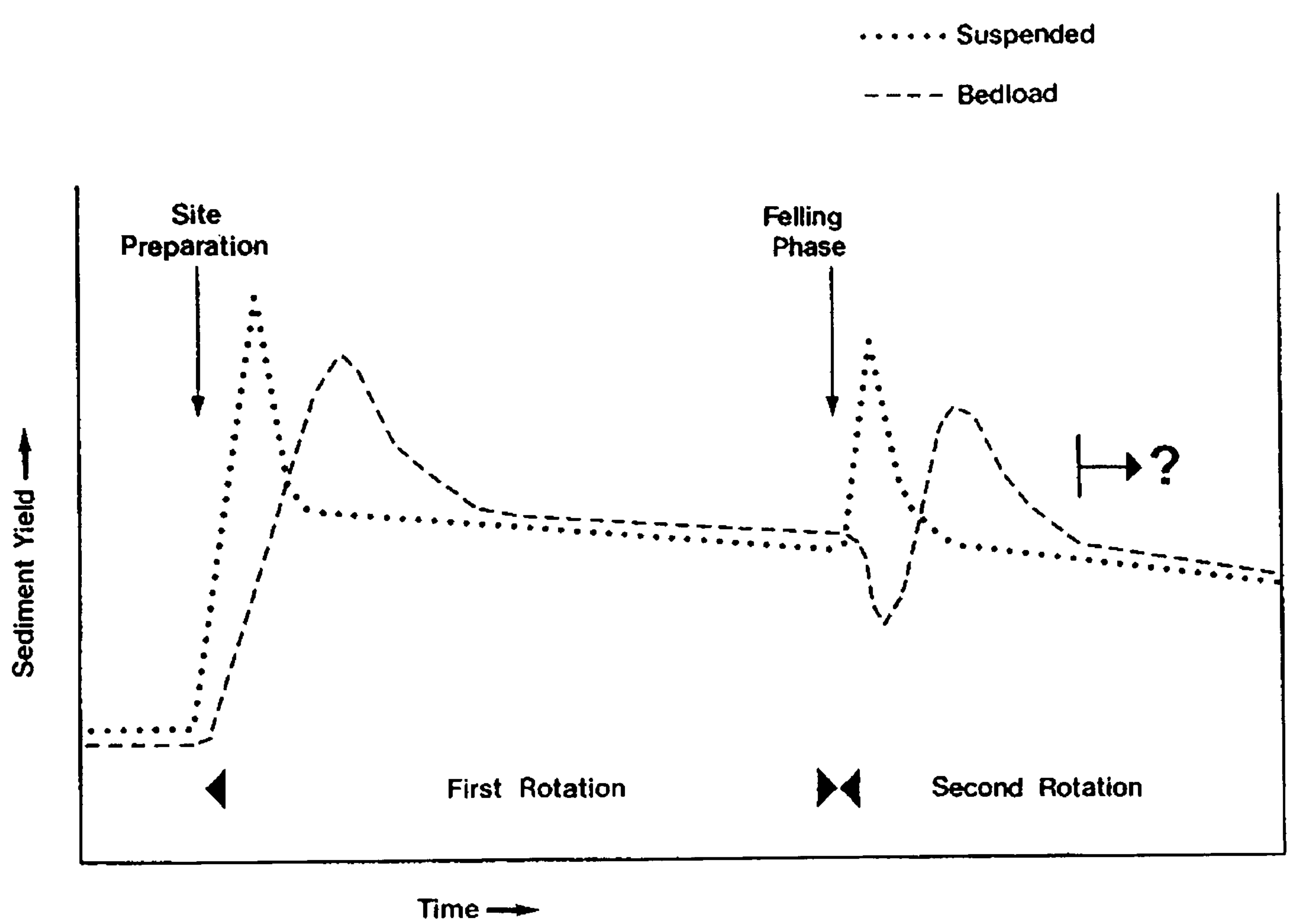


Figure 33.8 Summary diagram of upland stream sediment yields over the forest rotation

Figure 2.1. Summary diagram of upland stream sediment yields over the forest rotation (source: Leeks, 1992)

At Squaw Creek in Montana, Bugosh and Custer (1989) found that after a log jam burst, well after the felling period, bedload transport increased twofold immediately after the dam break, building a delayed bedload pulse into the system. Stott (1997b) showed bedload yields to be significantly higher under forested catchments, with yields varying proportionally with percentage forest cover. Stott *et al.* (1986) and Ferguson and Stott (1987) reported that bedload made up only 2% of total sediment outputs from the Kirkton and Monachyle catchments. Arkell *et al.* (1983) suggested six fold increases in bedload outputs under forestry. However, Johnson (1993) found little evidence for changing bedload regimes in the Balquhidder catchments, though he highlighted the difficulty of measurement with little specialist equipment or techniques available. Working on the granitic bedrock of Idaho, and in natural, rather than commercial forests, Megahan (1982) found that logging reduced channel storage capacity because natural storage points were destroyed by forest operations. Grant and Wolff (1991), working in paired catchments in Oregon on naturally forested catchments, found supplies of coarse sediment rose after harvesting by twelve-fold in steep streams capable of transporting load. Bedload outputs were supply limited, with most bedload moving completely though the system during the study. High levels of bedload output were maintained ten years after harvesting. Grant and Wolff (1991) highlight the importance of major threshold events in any geomorphological study, paired or otherwise.

The most important conclusion, especially from the felling phase, appears to be that mechanisms of felling can dramatically alter the impact and timing of bedload inputs. Although the conclusions of Megahan (1982) differ to the conclusions of Leeks (1992), this can be attributed to Megahan studying steep terrain, indigenous woodland, with Leeks examining plantation forestry.

Complex process-based computer modelling has been used to attempt to assess the effects of sedimentation on aquatic habitats. Ziemer *et al.* (1991) used the Monte Carlo model to assess the effects of different management practices in upland forestry, though the authors highlight the importance of being able to accurately simulate natural processes accurately. The simulation aimed to examine the effects of changing bedload regimes (as a function of the depths of scour and fill) on fish habitats and spawning beds. Harvesting was either 1% or 10% of catchment per year. The 10% logging strategy increased damage, albeit temporarily, to fish populations. The 1% strategy, however, suggests that current belief of dispersion avoiding damage may be incorrect, and that cumulative effects of small pocket logging may be greater than anticipated.

2.3. Geomorphic landforms

River channel bedform and floodplain planform are largely regulated by the pattern of sediment supply and transfer within the fluvial system. Any adjustment due to hydrologic variables, vegetation and mass movement within the system also depends on the existence, or lack of, a suitable sediment source. An adjustment in either quantity or distribution of sediment supply and transfer in the upper reaches of a fluvial system will therefore influence downstream morphology. The nature and extent of the change, and its geomorphic, social, and ecological consequences, will depend on the change of sediment parameters and the flow and transport competence of the channel itself. Kuhnle and Southard (1988) observed variation in transport rates in the laboratory, caused by the migration of long and low bedload sheets through the channel in medium transport rates. In high transport rates dune like bedforms occurred.

Changes in landform assemblages of gravel bed rivers is driven by flood magnitude, flood frequency and sediment inputs and gravel bed rivers can be classified into those limited by flow competence and those limited by sediment availability. Both types of streams exhibit landforms specific to the flow and sediment conditions that have created them. Where sediment supply is limited, deep scoured channels with significant exposed bedrock will predominate with bedload pulses moving quickly through the channel. In channels where flow is the limiting factor, and bedload is freely available, braids and bars are more common bedforms. These basic prepositions are based on the way in which bedload is transported by water on the streambed. Harvey (1987, 1991) working in the Howgills of Cumbria, showed that streams fed by large amounts of coarse sediment led to the development of unstable wide and braided channels. Conversely, lower coarse sediment inputs tend to create meandering, straight and stable channels. Harvey demonstrated that in the Howgills, active gullies and scars were responsible for providing sediment for braided and unstable channel patterns.

Froehlich and Starkel (1993) reported that forest clearance in the Himalayas resulted in a direct disturbance in the equilibrium of slopes and river channels. Frequency of mass movements in cultivated areas was 4-20 times greater than in natural forest areas. As such, channels in deforested areas underwent transformation by debris flow, making them deeper and wider. Differences between normal magnitude and major floods were also seen. With normal flood, streams are underloaded and with major floods became overloaded with coarse sediments (Froehlich and Starkel, 1987). Creation of unusually high riverbed rises (greater than normally observed by shifting bars) was also seen, as well as changes of longitudinal profiles greater than 50-100m long. A shift from incision to aggradation occurs, with the flow unable to rework the amount of coarse debris available.

2.4. Summary

The literature discussed describes some of the methods used and conclusions arising from studying sediment dynamics in gravel bed streams. The influence of forest operations is also discussed, though there has been little literature examining the impact of forestry on the flux of individual clasts in a gravel bed river. Particular reference has been made to coarse sediment and the use of tracers as an indicator of bedload transport. The stochastic nature of the travel distances of individual clasts has been highlighted, as well as the problems and opportunities of using tracer-monitoring programmes. The chapter also highlights the different approaches of monitoring bedload transport and demonstrates that research is undertaken at total yield scale, as well as examining the combination of forces necessary to entrain a single clast from a gravel bed.

Section 3: Methodology

3.1. Introduction

This section introduces and justifies the methods used for the experiments. It describes the techniques used for monitoring bedload characteristics, fixing channel features and change, measuring abrasion and determining hydrometric data.

The methodology section will present a justified choice of scientific method to achieve the project goals, in a manner influenced by the literature described so far. Details of the analysis of the data will be dealt with more thoroughly in the results section.

3.1.1. Project Aims

The project aims are repeated to justify the methods used: -

1 *To ascertain the effects of a change in land use in one catchment on the bedload characteristics of the main channel using a traditional paired catchment study;*

2 *to take an holistic approach to bedload transport, in studying total flux, size distribution and individual grain dynamics in the natural environment;*

3 *to assess how changing sediment production regimes affect the nature of bedload transport, and*

4 *to examine how forest operations can be improved further to minimise the impacts of timber-harvesting.*

To achieve these aims, methods were required to monitor (both accurately and repeatedly) bedload fluxes and the dynamics of gravel bed rivers over the medium term.

3.1.2. Data collection period

The project planning period started in September 1994 at Liverpool John Moores University. Data were collected between January 1995 and June 1997 at the Institute of Hydrology research catchments at Plynlimon, mid-Wales. Processing, analysis and writing took place from June 1997 to December 1997 and between September 1998 and August 1999.

3.2. Hydrometry and mapping

In order to precisely monitor and compare sediment parameters over the study period, both basic hydrometric and morphological data needed to be reliably collected. A high quality hydrologic data set was needed for the duration of the study, along with the ability to survey and resurvey critical points along the channel and banks. Methodology is presented from each experiment type.

3.2.2. Hydrometric monitoring

The collection of flow variables is integral to any examination of sediment transport. The essential transport mechanisms of saltation and rolling, outlined by Gomez (1991), are controlled by the energy coefficient exerted by the stream, with changes in discharge directly affecting stress, lift and drag coefficients on the river bed.

As part of the long term Plynlimon catchment experiment, The Institute of Hydrology (IH) maintain a flow monitoring network on Plynlimon, including flow gauging structures situated on the Nant Tanllwyth and Afon Cyff channels. Data are collected automatically using data loggers downloaded at 14 - 15 day intervals. Pressure transducers measure the depth in a stilling well adjacent to experimentally designed steep stream flumes (See Plates 3.1 and 3.2). The logger scans every 10 seconds and logs stage in the stilling well every 15 minutes from the hour, logging 96 times each day. A calibrated stage discharge relationship then provides the discharge in cumecs (m^3s^{-1}). An unbroken record for the period of study was available in a raw format in 14-

day segments. These segments were cut and apportioned as necessary to form the study periods that made up the duration of fieldwork. Table 3.1 shows the study periods and the dates between January 1995 and June 1997 on which critical fieldwork was undertaken. Analysis of the hydrometric data is given in section 4.1.

Plate 3.1. Flow gauging flume in Nant Tanllwyth.

Plate 3.2. Flow gauging flume in Afon Cyff.

Table 3.1. Flow characteristics for the study period, split into fieldwork sampling intervals

			Nant Tanllwyth		Afon Cyff	
Period name	**Period dates**	**Up to Julian day**	**Individual Dynamics**	**Bedload trap**	**Individual Dynamics**	**Bedload trap**
A	16-Jan-95 to 03-Feb-95	**18**	SEED	EMPT		
B	03-Feb-95 to 15-Mar-95	**58**	TRACE 1			
C	15-Mar-95 to 24-May 95	**128**	TRACE 2		SEED	
D	24-May 95 to 07-Jul-95	**172**		DIP		DIP
E	07-Jul-95 to 27-Jul-95	**192**		DIP	TRACE 1	
F	27-Jul-95 to 11-Aug-95	**207**	TRACE 3		SEED	
G	11-Aug-95 to 05-Oct-95	**262**		DIP		
H	05-Oct-95 to 15-Oct-95	**272**	SEED			DIP
HA	15-Oct-95 to 26-Oct-95	**283**				
I	26-Oct-95 to 15-Dec-95	**333**		DIP		
J	15-Dec-95 to 11-Jan-96	**360**	TRACE 4	DIP		DIP
K	11-Jan-96 to 18-Jan-96	**367**			TRACE 2	
KA	18-Jan-96 to 20-Feb-96	**400**		D/EMPT	SEED	D/EMPT
L	20-Feb-96 to 26-Mar-96	**435**	TRACE 5			
M	26-Mar-96 to 02-Apr-96	**442**			TRACE 3	DIP
MA	02-Apr-96 to 03-May-96	**473**		DIP		
N	03-May-96 to 02-Jul-96	**533**	TRACE 6	DIP		DIP
O	02-Jul-96 to 01-Oct-96	**624**	TRACE 7	DIP		DIP
P	01-Oct-96 to 19-Nov-96	**673**		D/EMPT		DIP
Q	19-Nov-96 to 10-Dec-96	**694**	TRACE 8	DIP		DIP
R	10-Dec-96 to 14-Mar-97	**788**		DIP		DIP
S	14-Mar-97 to 09-Apr-97	**814**	TRACE 9	DIP	TRACE 4	DIP
T	09-Apr-97 to 02-Jun-97	**868**	REMOVAL 10	DIP	REMOVAL 5	DIP

Data were analysed in terms of both total discharge and excess flow over threshold flood levels. Thresholds were determined by personal communication with IH employees and based on experimentation with local thresholds for entrainment. Selection of flow thresholds by Moore and Newson (1986) was undertaken in the same channels using evidence derived from observed thresholds using Helly-Smith samplers. These thresholds were different for the Nant Tanllwyth and the Afon Cyff, with no thresholds under the 1.0 m^3s^{-1} used. However, analysis of thresholds under 1.0 m^3s^{-1} in the Afon Cyff showed that sediment mobilisation did occur. It was therefore decided to use the same thresholds for both rivers, and additionally extend thresholds in the Afon Cyff to represent its higher discharges.

Parameters of time (hours over 0.3, 0.5, 1.0, 1.5 and 3.0 m^3s^{-1} flow) and discharge (total volume (in '000 m^3) over 0.3, 0.5, 1.0, 1.5 and 3.0 m^3s^{-1})) were calculated using Microsoft Excel spreadsheet macros.

The actual threshold values were not the only choice for the analysis of threshold events. Several approaches have been taken to the analysis of flood events, these include:

1. time over threshold;
2. number of events over threshold;
3. volume over threshold and,
4. individual peak flows.

All of the approaches are viable in terms of comparing floods over time and between catchments, as flow records show hydrograph shape is consistent, allowing for time and discharge analysis. Testing of relationships was undertaken and the use of the volume over threshold was chosen both for its best statistical correlation and for physical correctness. Volume over threshold was chosen as a measure of the stream's capacity to transport and includes the measures of time and overall peaks. Using only a time over threshold does not include any measure of how much the threshold was exceeded by. Using number of events over threshold in turn gives no indication of how long the peaks lasted for: this time factor has a significant control on their geomorphological effectiveness (Gilvear and Harrison, 1991).

3.2.3. Tracer mapping techniques

A survey method was required to map tracer locations and channel banks which had to satisfy the needs of accuracy, practicability and reliability. The conditions in which the fieldwork was undertaken largely governed the mapping method chosen. Both channels were small in size, the Nant Tanllwyth averaging less than 2 m in width and the Afon Cyff less than 4m. Methods considered and subsequently rejected included: EDM, level, theodolite, and horizontally laid tape. The use of an EDM was initially an attractive option, providing extremely accurate and repeatable readings. However, it was impractical both for use on solo visits and for the conditions in the Nant Tanllwyth where trees and overhanging branches made surveying from limited fixed points to the channel impossible. The use of a level and tape was rejected for the same reasons, with overhanging trees obscuring the siting of the level at many points. A further option considered was to align a tape parallel with the channel and measure points adjacent and perpendicular to the line to determine distance. This was rejected due to lack of reliability in producing 90-degree angles and subsequent loss of accuracy in mapping both lateral and downstream position of tracers in the channel.

The final method also needed to fulfil several criteria:-

1 The method had to be operable by one person, as the bulk of fieldwork was to be done alone;

2 it needed to be durable and as invisible to the public as possible, as both forest operations and a public footpath ran alongside the Nant Tanllwyth;

3 it needed to be accurate, as previous work (Ergenzinger and Conrady, 1982; Hassan, 1990) had demonstrated the relative stability of some tracers *in situ*, and

4 it needed to be rapid and repeatable, so as to allow traces of up to 200 clasts per channel to take place in limited periods both in practical fieldwork terms, and between winter flow events. With winter daylight hours limited, a rapid but accurate reconnaissance was essential.

Taking account of the various constraints, a triangulation method (the two-tapes method) was developed for use in all tracer surveys in the Afon Cyff and Nant Tanllwyth. This provided a technical solution to the mapping problem for accuracy and reliability, as well as accounting for the time, personnel and financial constraints of the project.

The method is outlined below. Differing terrain present in the Afon Cyff and Nant Tanllwyth meant that slight variations on the setting up of the system were used, with an extra level of complexity, and therefore error, present in the Nant Tanllwyth. The methods are described respectively.

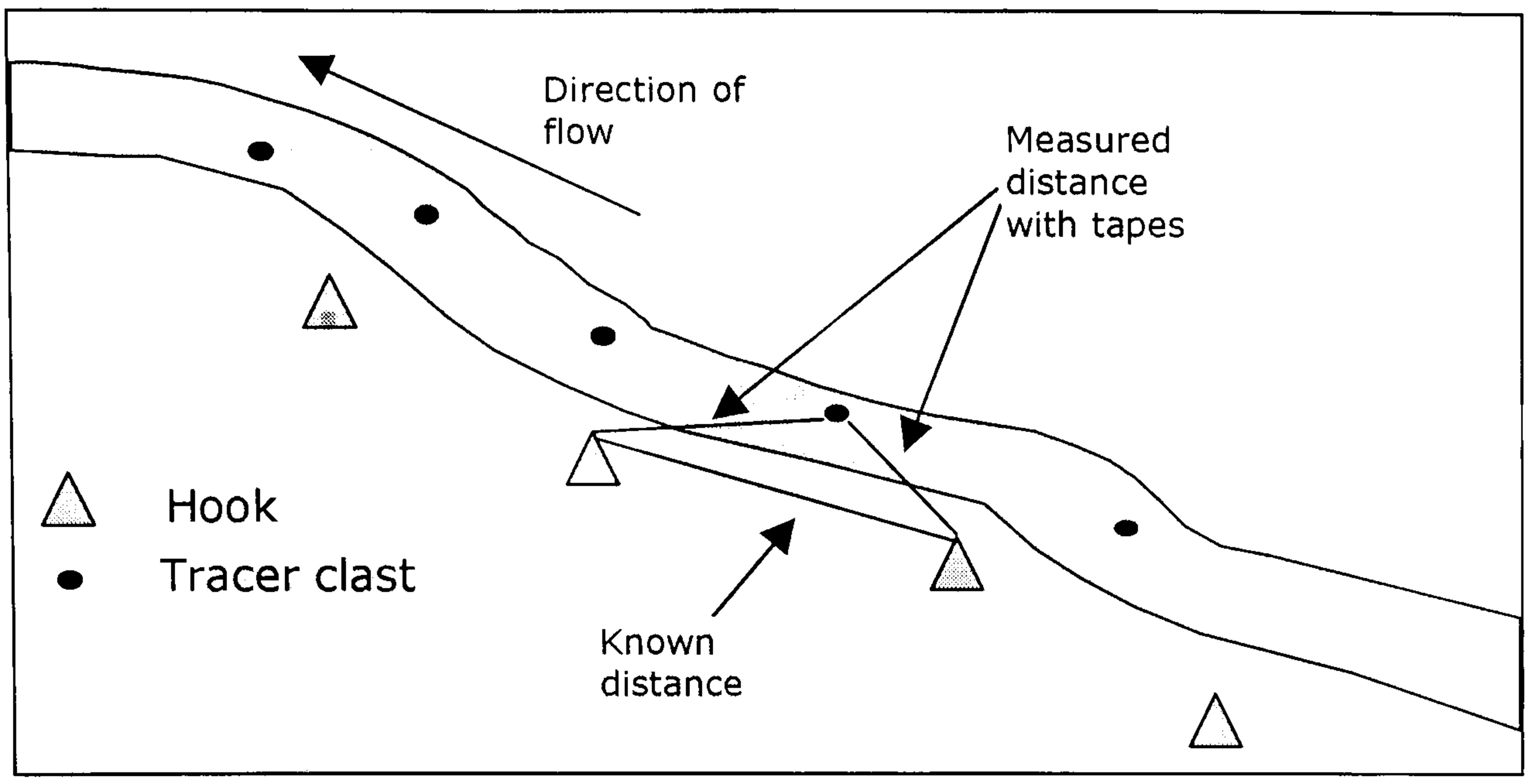


Figure 3.1. Diagram showing morphological mapping and location

The triangulation 'two tapes' technique chosen works on a simple method. The ends of two tapes are fixed at known benchmarks on the channel side, as shown in Figure 3.1. Any new point, say point x, can be mapped by stretching each tape to point x and measuring and recording the distance from each benchmark. With the distance from each benchmark known, it was then possible to define Cartesian co-ordinates for the new point x. A series of regularly spaced benchmarks along the channel banks could then map features in the channel, channel banks and any tracer location. The positions of the benchmarks was fixed at the start of the project, with standard levelling techniques (Clancy, 1991) used to fix their XYZ co-ordinates. As noted above, the siting of these benchmarks were constrained, particularly in the forested Nant Tanllwyth, by bankside vegetation.

Using Microsoft Excel macros, Cartesian co-ordinates were calculated as shown in Figure 3.2, in an excerpt of the calculation spreadsheet. The table below is shown as an example only.

Errors from the method were dependent on a number of variables:

1. the surveyed accuracy of the benchmarks themselves;

2. any stretch of the measuring tapes;
3. measuring error in terms of the original location of the pebble, and
4. measurement error due to field worker error.

The benchmarks were surveyed in at the beginning of the study. The distances between benchmarks and then distances between hooks were measured and re-checked. The distances between hooks used to calculate the pebble positions were always directly measured distances (marked known distance on figure 3.1). All distances between hooks were found to be ± 5 mm after re-measurement. This eliminated any error associated with deriving the position of the hooks from benchmarks in the Nant Tanllwyth. Tapes were tested in both summer and winter measuring between benchmarks: no differences between measurements were found and this source of error was eliminated.

The main errors were identified as properly measuring the originally located pebble position and the operator error. The errors in locating the exact position of the pebble are near impossible to quantify. On most occasions, location of the tracers pebbles was straightforward and the resting position was easily identified. However, in cases of deep burial and occasionally in the case when two pebbles were located at the same point, the excavation caused the movement of the pebble out of the dredged hole. In this case an error was possible, but not quantifiable. With the deepest excavations leading to holes around 400mm, it is possible that the measured position was up to ± 200 mm from the true buried position. In practice, these deep excavations happened rarely and in any case, it is likely that the original signal (where the centre of the hole would have been made) indicated the correct location. The second error was operator error. This could have occurred due to misreading the tapes. Care was taken to always read the tapes on the vertical above the pebble (ascertained using the Magnotrack locator) but repeated surveys at the same point showed up to a ±50 mm error. This figure however is slightly misleading as errors tended to occur in a cross-stream rather than downstream direction due to the mapping method. With analysis of downstream movements most crucial, effective errors in distances travelled (between two traces) remained at ±50 mm. Thus the effect of the error was not cumulative.

1	2	3	4	5	6	7	8	9	10	11	12
Bank	D/S BM		U/S BM		Dist	Bear	East	North	New bearing	EASTING	NORTHING
Bank	C	477	D	1359	14	292.5	966	1002	6.43	966.48	1007.05

Column 1	Designate a bank description, or tracer code.
Column 2-3	shows downstream benchmark code (known co-ords) and tape length to mapped point
Column 4-5	shows upstream benchmark code (known co-ords) and tape length to mapped point
Columns 6-9	Are automatically pasted by macro depending on the value of the lower hook point, and designate the distance between hooks, bearing from North between them, and the Easting and Northing of the downstream hook.
Column 10	calculates the new angle between the downstream hook and the survey point.
Columns 11 and 12	finalise the new Easting and Northing co-ordinates.

Figure 3.2. Notation for mapping and tracer relocation

AFON CYFF

The channel reach selected for study in the moorland Afon Cyff was approximately 325 m, with no obstacles to surveying the channel. Benchmarks were fixed at approximately 15 m intervals and between 0.50 m and 1.50 m from the bank side. Benchmarks consisted of 0.6 m wooden stakes driven into the ground, leaving approximately 0.1 m of the top exposed. Each benchmark was allocated a letter (from A to V) and marked with a steel plate and a hook was fixed in the stake to allow a tape to be securely attached to it. These benchmarks were subsequently used as the triangulation points for all mapping and tracer co-ordinates. Using standard levelling techniques (Clancy, 1991) each benchmark was assigned Cartesian XYZ co-ordinates based on (0000, 0000, 0000) as the top right corner of the bedload trap. These were calculated and recorded to 0.01 m. An example of the field survey notation for tracer location is shown in Figure 3.3 below. This notation was used AFTER the benchmarks were levelled in. In reality, the field notebook would also contain columns for notes, as well as a description of what was being mapped in each row.

Lower Benchmark	Distance	Upper benchmark	Distance
A	6.00 m	B	5.00 m

Figure 3.3. Recording notation during tracer location

NANT TANLLWYTH

The afforested Nant Tanllwyth presented an additional problem. With the trees present around the channel, it proved impossible to position benchmarks where both full coverage of the channel and level sighting was possible. Instead, the trees on the north side of the channel (not to be felled) were utilised as hook triangulation points, with a separate network of benchmarks installed as in the Afon Cyff, but not providing hooks for channel measurement. The tree hooks were then surveyed from the benchmarks to obtain the channel mapping co-ordinates that could be levelled without interference from trees. The XYZ co-ordinates of the tree hooks were then surveyed directly from the benchmarks and it was these hooks, as with the Afon Cyff, for which all triangulation was undertaken.

3.2.4. Stream survey

At the start of the project, it was envisaged that a detailed survey of the channel banks of both rivers would be undertaken. Based on the experience of previous studies (Davis and Gregory, 1994), erosion and damage to banks was anticipated in the afforested Nant Tanllwyth during forest clearance operations. However, in tandem with this study and over the same period, a comprehensive study into bank erosion in the channels (Stott, 1999) revealed mean erosion rates to be only 30 mm yr^{-1}. Mean bank erosion rates post-harvesting increased to 65mm yr^{-1} on unfelled banks and to 95 mm yr^{-1} on banks from which trees had been clearfelled. However, these bank erosion rates were significantly less than the standard error of the two-tapes measuring technique. The technique was subsequently not used for the study of channel bank erosion.

3.3. Grain size distributions

Monitoring of bedload was undertaken at repeated intervals throughout the project to assess the grain size distribution of the channels. It was hoped to use grain size distributions as a background to any change in sediment transport flux and to assess change, which might affect salmon spawning and channel stability. Several methods were attempted to monitor changing grain size distributions in the channels.

1 Bed photography;
2 surface counts;
3 channel bulk samples, and
4 freeze core samples.

Due to unsuccessful attempts at the use of photography, this technique has not been included in the thesis as a method of deriving grain size distributions. Several sets of photographs were taken through the catchment during the felling period at fixed locations, and initial testing using digitised measuring techniques were promising. Problems arose however with ground truthing the results and it proved impossible to correlate distribution of size measurements of sieved data to those derived from photography. The technique was originally promising as the method is non-destructive and the shape distribution in the Nant Tanllwyth and Afon Cyff suggested that the method could be successful.

Photographs were taken initially at sixteen sites along the bed of the Nant Tanllwyth and at ten sites along the Afon Cyff. Images were obtained using a tripod at fixed height above the sediment surface, photographing vertically to the bed. At each point two frames were taken at different shutter speeds. Each photograph included a 100 cm rule uniquely marked to correspond with notes taken of site details. Sites were mapped using the two-tapes method to allow relocation of the sample points on the bed.

After processing, colour photographs were scanned into Adobe Photoshop for correction and improvement. Photoshop allowed improvements in light and contrast to the photographs which were often taken in difficult conditions. Using Photoshop, all visible pebbles were measured and recorded along the two visible axes, based on the dimensions of the rule included in each image. A frequency distribution was then drawn up. To ground truth the data, three areas in the lower Nant Tanllwyth were used to photograph, surface sieve and grid sample. In drawing up the distributions made by the separate methods, it was impossible to match the image derived distributions with those from grid sampling or sieving.

The method may have benefited from a different approach at the ground truthing stage. Instead of relying on distributions (the ultimate derivation) for ground truthing, a more basic unit of study could have been attempted, whereby an area is photographed and a number of clasts (~100) could have been marked in the photo. These clasts could then be measured individually to match up with the photo derived measurements of the same clasts to allow a closer examination of where the variations and errors were derived.

3.3.1. Surface counts

Surface counts were undertaken using a derivation of the Wolman method (Wolman, 1954) which represents the aereal distribution of the size range over the bed. Random samples of 100 pebbles in a reach were taken and the intermediate axis was measured on removal. This method has the advantage that there is no requirement for sieving, although Wolman (1954) points out that median diameter is larger than that obtained using a sieving technique. It is, however, representative and can be used in comparisons with other channels of similar size range. Consistency of reach length is required for comparison, and as both reaches were of similar length, the same number of samples could be taken from each.

The technique chosen used a grid system of sampling. Several methods were trialled, including a specially constructed table from which paint was dipped onto the clasts from above. However, this method restricted the area from which samples could be taken. The final system chosen used a tautly stretched tape laid over the sediment surface and samples were taken on 0.2 m intervals on the tape. A 2 m square was constructed and nodes taken every 0.2 m across the square. Samples were made at 4 points in each channel approximately 100 m spaced apart. This fulfilled the random selection of the count and removed the difficulty of selecting clasts without looking (using the toe of the boot method) where picking up smaller clasts is problematic.

3.3.2. Bulk Samples

At five regular intervals during the course of the fieldwork, bulk samples of sediment were taken at 5 fixed points in each channel. Samples were shovel sampled at *exactly* the same point on each occasion, and were bagged, dried and removed to the laboratory for sieving and analysis. Samples were firstly weighed wet, then dried, sieved and the size fractions weighed individually. It was hoped the technique would allow the assessment of the degree of variability in bedload distributions throughout the channel. Selective sediment loss of fines was thought to be a problem (Thoms, 1992) as the shovel passes through the water and fines were swept off the shovel (Petts, 1988). The variation in each sample, however, meant that changes could not be detected in such a small sample, and these samples were eventually used just to give overall D_{50} rather than assessing change over time. In addition, the method meant that selective sampling of sediment, with both very large and very small sections of the distribution left under-represented. Removing samples large enough to give true distributions (Church *et al.*, 1987) would have simply been too destructive in such a small channel as the Nant Tanllwyth, where tracing and trapping techniques required maintaining the channel in as natural condition as possible. Church and Wolcott (1987) state the largest clast in the sample should make up no more than 1 % of the mass of the total sample.

3.3.2. Freeze coring

To obtain samples that were both deeper and less prone to any selective sediment loss, freeze coring was undertaken in conjunction with the Institute of Hydrology (Marks, 1996). The method can collect bedload and associated substrate up to a depth of approximately 0.3 m and full details of the method are available in Petts *et al.* (1989).

The basic method is as follows. A hollow metal stake is driven into the riverbed to the required depth (approximately 0.4 m) and into the stake a liquid CO_2 is pumped via a pipe with a number of evenly distributed nozzles. The surrounding gravel then freezes and forms a cylindrical core of substrate around the stake, which can be winched from the riverbed and removed for analysis. After removal, sediment was divided into 0.1 m sections and each sieved separately.

3.4. Sediment Yields

The total bedload output of each stream was determined using bedload traps at the lower end of each channel reach. Each trap was resurveyed at the time interval shown in Table 3.1. Several studies, notably Moore and Newson (1986), had used the bedload traps installed within the catchments and they provide a valuable long-term record of the bedload outputs of the two channels. To fully realise the project aims and to obtain a dataset of suitable quality, it was deemed necessary to upgrade the bed load traps for the purpose of the study.

Previous work by IH at Plynlimon (Moore and Newson, 1986, Leeks 1992) had measured total flux by emptying the bed load trap on each measurement using a JCB bucket, the sediment removed being emptied onto a stake adjacent to the trap (see Plate 3.3).

Plate 3.3. Nant Tanllwyth bedload trap: JCB excavation onto measuring spike.

The stake was fitted with partition boards to allow one eighth of the sediment cone to be split. This sample was then wet weighed, and multiplication of this mass by eight gave a total flux for that period. There were several limitations with this method: -

1 The availability of heavy machinery for each survey;
2 a loss of accuracy, both from failure to completely empty the trap and in incorrectly estimating the proportion of the sediment cone, and
3 the availability of manpower for each survey.

It was therefore decided to utilise the existing bed load traps and to upgrade them to a more accurate and usable system. A system was required to meet the needs of the study, and especially important was that resurvey needed to be accurate and carried out using the minimum of pre-planning or expense.

The process of dipping of the traps inevitably had minor associated errors. The traps themselves, due to their rigorous construction were relatively free of errors. They were built of concrete, had immovable monitoring rails and the dipping sticks were constructed from carefully machined steel parts - this ensured the stick was vertical when meeting the sediment surface. The main error therefore was the possible movement of the dipping stick when contacting the sediment surface, either through slight sliding on a smooth pebble, or by moving into a soft granular sediment surface.

Errors were estimated by repeat monitoring of the trap on the same day. Of the 144 points on each dip, errors in individual readings after repeat dipping were shown to be ± 40 mm, with more than 75% of these errors ± 10 mm between first and second dip. Errors were distributed normally and lead to the overall error in bedload yield to be less than 35 kg for each dip.

3.4.2. Construction of bedload traps

Existing bedload traps measured 4 m square by 1.5 m deep and traps were constructed of reinforced concrete, with smooth straight walls (see Plate 3.4). The lip at the front of the trap was designed to ensure sediment did not pass through the trap to the channel below. Confirming the traps worked correctly in practice presented a challenge. Field observations below the traps suggested little sediment was passing through in the Nant Tanllwyth, but due to the initial design siting of the Afon Cyff trap, some sediment seemed likely to pass through at high flows, or during high sediment mobilising events. In practice, traps were assumed not to be leaking large volumes of sediment based on the following observations:

1. traps were never observed to have filled up to the lip of the exit rim;
2. traps were emptied when approximately half full, to allow for the capture of large events, and
3. observations downstream showed that no significant sediment accumulations took place within 50 m of the trap.

The design of the bedload trap in the Nant Tanllwyth is shown in Plate 3.4. Upgrading of the traps was undertaken by constructing fixed metal runners on which to mount a movable template for fixing a grid of 144 positions over the trap surface. Using a specially designed and manufactured movable bridge for measurements, this grid enabled a measuring stick to be lowered at fixed positions over repeated visits to the trap. The dipping of the trap enabled a three dimensional image to be drawn of the bedload trap surface on each visit and a calculation made of the total volume change of the trap from the last visit. The technique is explained below.

3.4.3. Trap measurement and maintenance

Dipping the bedload trap was a three-stage process: installation of template, location of the dipstick into the template and reading of depth measurements. To locate the same precise point at which to dip for each visit, the template bar had to be positioned at fixed points. These were fixed using small studs on the runners in the bedload trap. On locating the template into one of its nine positions, the dipstick was guided into two slots on the template to ensure a vertical measurement. This vertical position was crucial to measurement accuracy, as any variation would firstly measure an incorrect angle and thus a greater distance to the sediment surface. Secondly, if the dip-stick were to locate at the top of a sediment clast, it might slip down below its true position. The first point of contact of the dipping stick, as it was lowered through the template, was considered the sediment surface. With the possibility of particle winnowing and a different surface/sub-surface distribution present in the bed load trap itself, adherence to this procedure was seen as central in determining small levels of change within the traps. Test experiments showed that larger particles present in the trap introduced further error, which was a particular consideration in the Afon Cyff. Readings were processed into a contour map of the sediment surface. An example is shown in Figure 3.4 below.

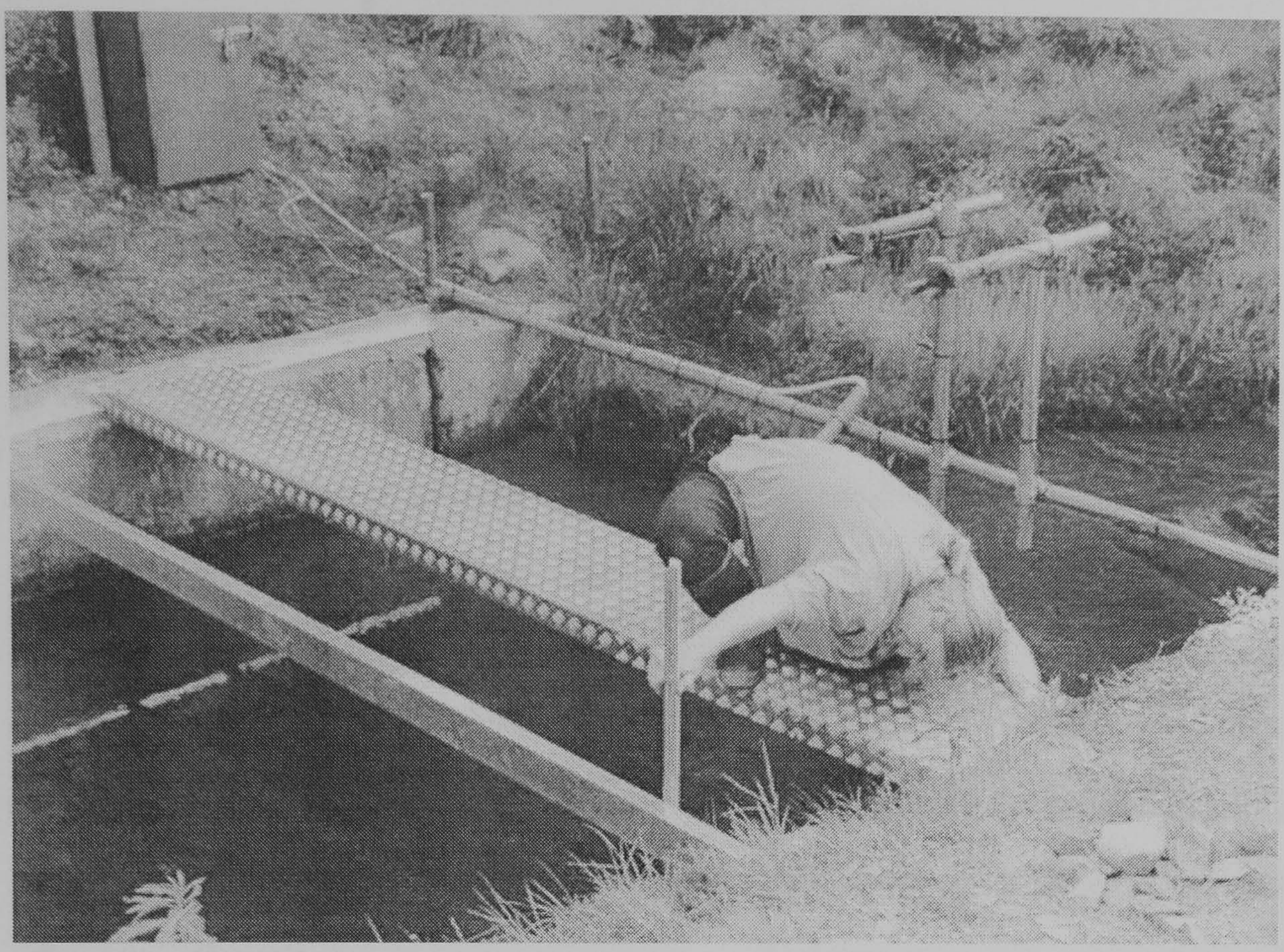


Plate 3.4. Survey method for Nant Tanllwyth and Afon Cyff bedload traps.

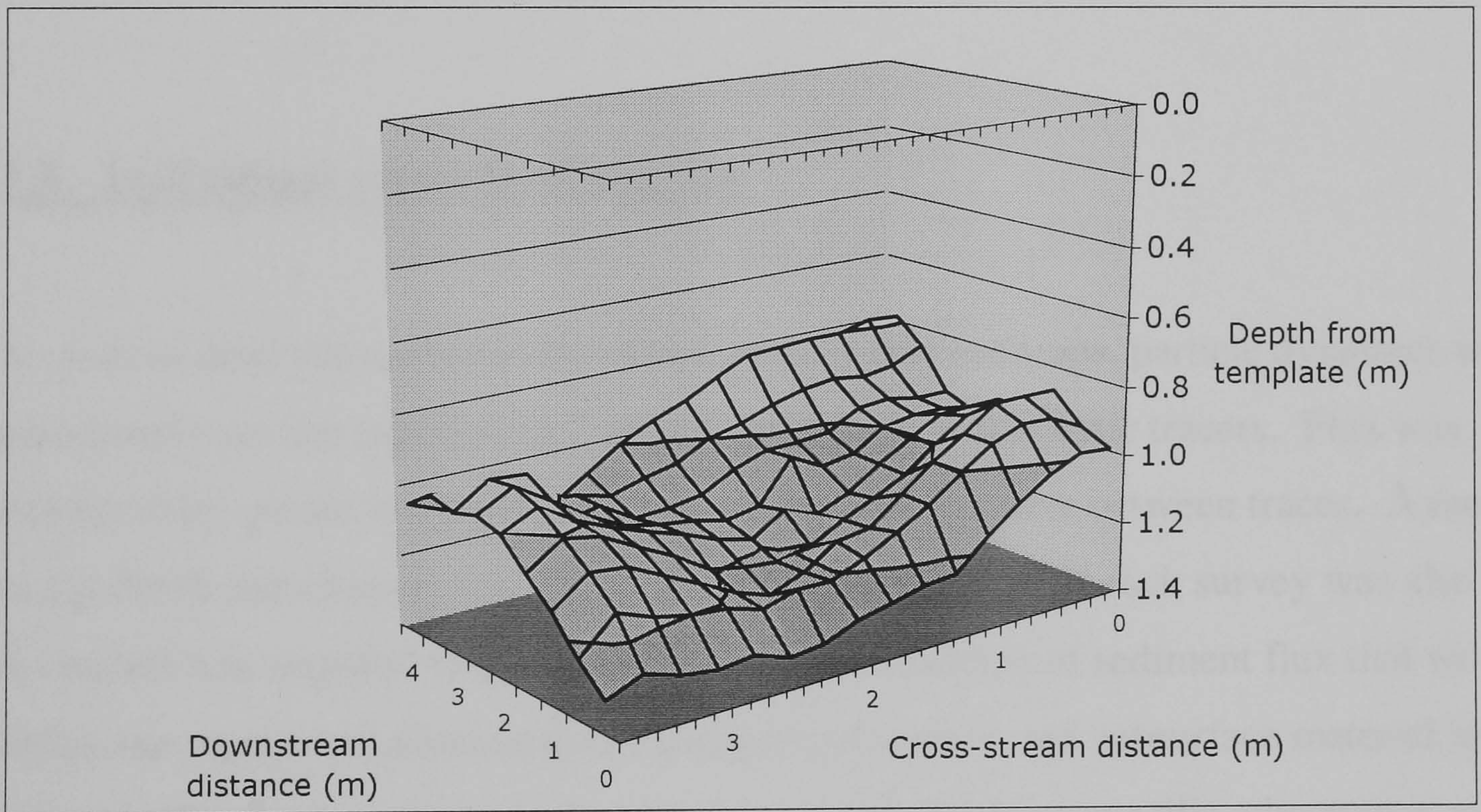


Figure 3.4. Diagram of sediment surface from dipping bedload trap.

On two occasions during the study the bed load traps required mechanical emptying after heavy sediment accumulation. This process required hiring a JCB digger (Plate 3.3) and emptying bedload in a pile adjacent to the trap. The sediment cone was positioned sufficiently far from the trap to avoid sediment washing back out into the trap or channel again.

3.4.4. Analysis of trap data to estimate yields

With several measurements taking place between each excavation and emptying, a method of estimating total sediment yield in each period was required. Using two contour maps of the bedload trap, a volume of sediment deposited or removed from the trap could be calculated using a spreadsheet solution. The difference in volume between the first and second readings, multiplied by the density of sediment gave a total output of material during the measuring period. These volumes could then easily be related to time and streamflow conditions. Density was derived using bulk samples removed directly from the bedload trap. Density was determined by taking a known volume of wet sediment, drying it and weighing the dry material. Bedload in the Nant Tanllwyth bedload trap had a density of 1.69 t m^2 whilst in the Afon Cyff, density of trapped material was 1.83 t m^2.

3.5. Individual particle dynamics

As well as determining total flux of sediment in bedload traps, particle dynamics were monitored over the experimental period using passive magnetic tracers. Flux was estimated by measuring the distance moved by each particle between traces. A record of the depth and channel position of the tracers at the time of each survey was also kept. A method was required to give an accurate representation of sediment flux that would define the nature and distribution of transport of surface and subsurface material in the channel. The tracing methods discussed in section 2.1 have specific advantages and disadvantages and a technique was required to fulfil the dual needs of yielding quality data and being a practical solution for one or two field workers. The passive tracer system used by Hassan *et al.* (1984) and Wathen (1995) which involved implanting ferrous material or magnets into natural clasts, was chosen to allow a large quantity of tracers to be manufactured on a limited budget. Bunte and Ergenzinger (1989) state:

Choosing the appropriate tracer technique for the question of research and nature of the site is not only dependent on pecuniary matters but on the availability of technical/electronic instrumentation and know-how.

Thus, the technique needed to be reliable and usable by initially inexperienced and unsupported field workers.

3.5.1. Tracer design and planning

To represent sediment fluxes Dietrich *et al.* (1982) maintained the need for any tracer population to mirror the size distribution of the bed. Hassan *et al.* (1992) highlight the discrepancy between tracer distributions and actual channel distributions in many previous experiments. In addition, the question of selection of the type of size distribution also arises. The D_{50} surface and D_{50} subsurface show different values and there are different freeze coring and Wolman distributions in the samples from the Nant Tanllwyth and Afon Cyff. Difficulty persists within tracing in geomorphology, in that the tracer distribution will always have a skewed size range due to the lower limits of the size of clasts that can be successfully tagged. The choice of size range was a crucial consideration in the experimental design and one that would ultimately affect the analysis and prediction of sediment fluxes in both channels. To attempt to represent the entire distribution was impossible due to the logistical constraints of constructing sufficient tracers in the smaller size ranges. In addition, techniques available did not allow for successful tagging of clasts smaller than 8 mm. The final distribution of the tracer particles is shown in section 3.5.4 below.

The success of any passive tracing system is based upon the ability to re-locate tracers in the field. This depends on the strength of the magnetic field emitted by the tracer, the sensitivity of the search instrument, and the background magnetism of the search area. Testing and discussion (Wathen, pers comm) led to using small cylindrical and cubic magnets, varying in size and strength of field emitted. Larger clasts could be fitted with the biggest magnet, type *a* (Cylindrical, depth 7 mm, diameter 10 mm), with smaller clasts having size *b* (cubic, 4 mm, 4 mm, 8 mm) and smallest clasts type *c* (4mm, 4mm, 2mm) installed. The decision as to which magnet to use was often subjective, but was largely based on both the size and shape of the tracer clast, and was in practice often governed by particle c-axis.

3.5.2. Tracer construction

All tracers were manufactured using clasts from the channel in which they were subsequently used. Clasts were selected at random from the surface of each channel. Around 95 % of bedload material in the Nant Tanllwyth was composed of shales, suitable for tracer manufacture. Approximately 5% of material (by mass) in the Nant Tanllwyth was a hard glacially derived granitic rock, which proved exceptionally difficult to drill successfully and therefore these clasts were not used to manufacture tracers.

Tracers were constructed using the following process: -

1. Clasts were selected for drilling based on bed distribution (section 1.3);
2. clasts were sorted into size classes for construction with different magnet size;
3. clasts had a hole drilled into the thickest section using a drill stand and high-speed masonry drill bit, without hammer action (this was found to quickly weaken and shatter the clast);
4. the tracer was cleaned and dried, and a layer of epoxy poured into the hole;
5. a magnet was inserted into the wet epoxy, with the hole flooded with epoxy with approximately 3 mm recess;
6. a waterproof label was inserted into the end of the hole, covering the magnet embedded in liquid epoxy, and
7. after a one-hour drying period, further epoxy was added to cover the label and fill the hole flush with the rock surface.

An example of a completed tracer is shown in Plate 3.5. Tracers were tested in a for waterproofing and breakage. No problems were found in the tested tracers, although one batch was found to have rapidly corroding labels, possibly due to incorrect waterproofing of the labels, or the epoxy mixture having changed in manufacture. This was discovered after tracing was undertaken.

After manufacture, all pebbles were weighed, measured (a, b and c axes) and were given a small colour spot on one side. The public right of way along the Nant Tanllwyth precluded the use of brightly coloured markers as attempted by Takayama (1963), Thorne and Lewin (1979) and Wathen (1995).

Plate 3.5. Labelled tracer clast in Nant Tanllwyth (above) with temporary marker pebble (below)

3.5.3. Tracer seeding

Significant importance had been attached to the initial, or *seed* location, of the tracers in the stream channel. Much of the work pioneered by Schmidt and Ergenzinger (1992) and furthered by Stott (pers comm) in developing a clast that does not require digging for relocation (radio tagged tracer) has been driven by the advantage of allowing a tracer to start from the natural position in which it rests. Tracers in this study were seeded in a line of either 5 or 10 across the channels in both riffles and pools. It was anticipated that this would provide the most rapid form of entrainment and yield useful data on the competence of flow in transporting bedload. Tracers were seeded along the entire length of the channel with lines equally spaced approximately 30 m apart. This was done in an attempt to represent and quantify transport parameters throughout the study reach. Seeding was undertaken by pushing the tracer into the gravel using the sole of a rubber boot, this was to ensure that tracers had as natural starting position as possible.

3.5.4. Tracer size distribution

Bed grain size distributions for Afon Cyff and Nant Tanllwyth are discussed in the Plynlimon section 1.6.2. Various approaches have been used to construct a size distribution for tracers to use in an experimental stream channel. These can be split into manufactured (concrete or other material) tagged tracers, and natural (local bed material) tagged tracers.

Studies attempting physical modelling of entrainment, transport and deposition parameters have found the control given by the use of manufactured tracers invaluable. The method allows modellers to better calculate conditions at times of entrainment, and minimise controlling variables by manufacturing large numbers of tracers of predetermined size and shape classes.

A number of experiments aiming to determine bedload characteristics of specific streams, rather than investigating the physical forces involved in entrainment and transport of individual clasts, have used natural bed material. This material, subsequently tagged, should better simulate natural conditions of entrainment and transport through a channel. This experiment aimed to examine natural transport conditions within two specific channels, so tracers taken from the channel were deemed more appropriate. It was intended that the tracer D_{trac} sample should represent the size distribution of sediment in each channel. In reality however, D_{trac} could only represent one constituent part of the distribution, with overall sediment distributions differing with surface and subsurface conditions, as well as possibly differing due to different stages of armour progression. Thus, an approximation of the surface size distribution was made. Bulk sediment samples and freeze core samples taken from the Afon Cyff and Nant Tanllwyth do not adequately represent the size ranges of the bed surface material. In order to best represent the bed surface distribution random counts based on

Wolman (1954) at both exposed and underwater points within the channel were used. Bulk samples removed from the bedload trap contained a large proportion of fines, unsuitable for tracing, and were not applicable for determining tracer distributions for the individual particle tracing experiment.

The distribution of the tracer sample in the Nant Tanllwyth is shown in Figure 3.5, and for the Afon Cyff in Figure 3.6.

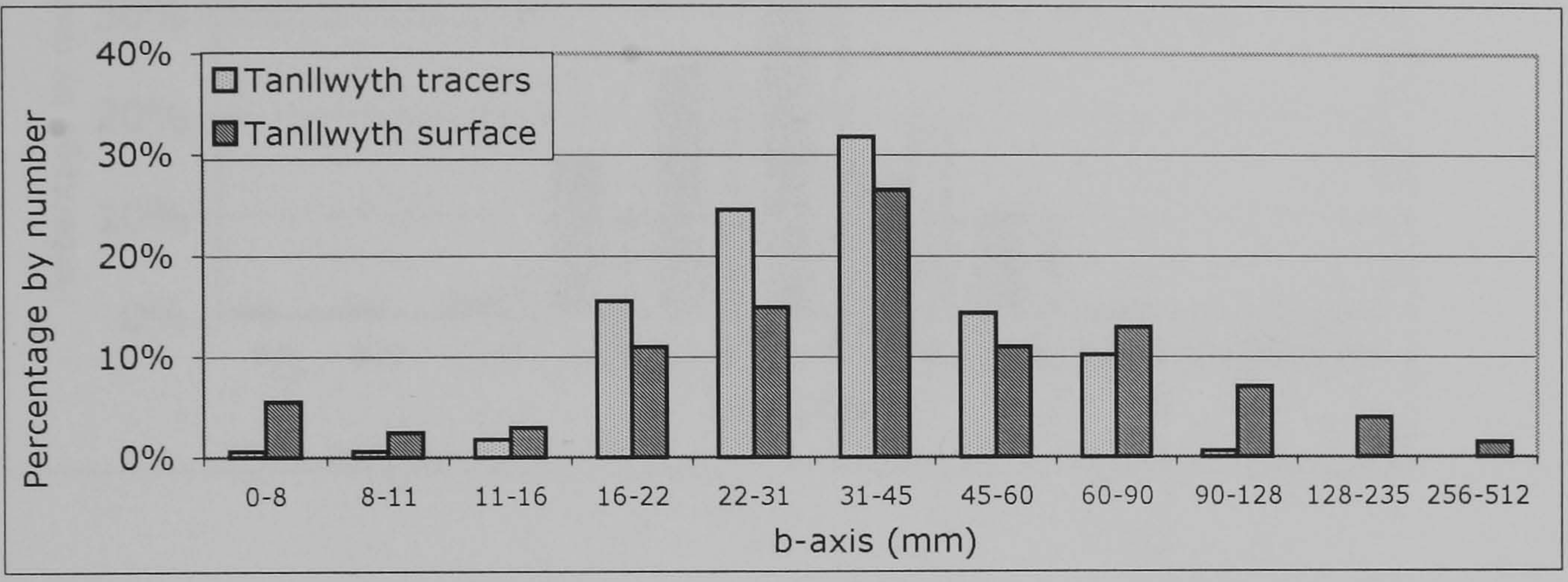


Figure 3.5. Tracer and surface size distributions for the Nant Tanllwyth

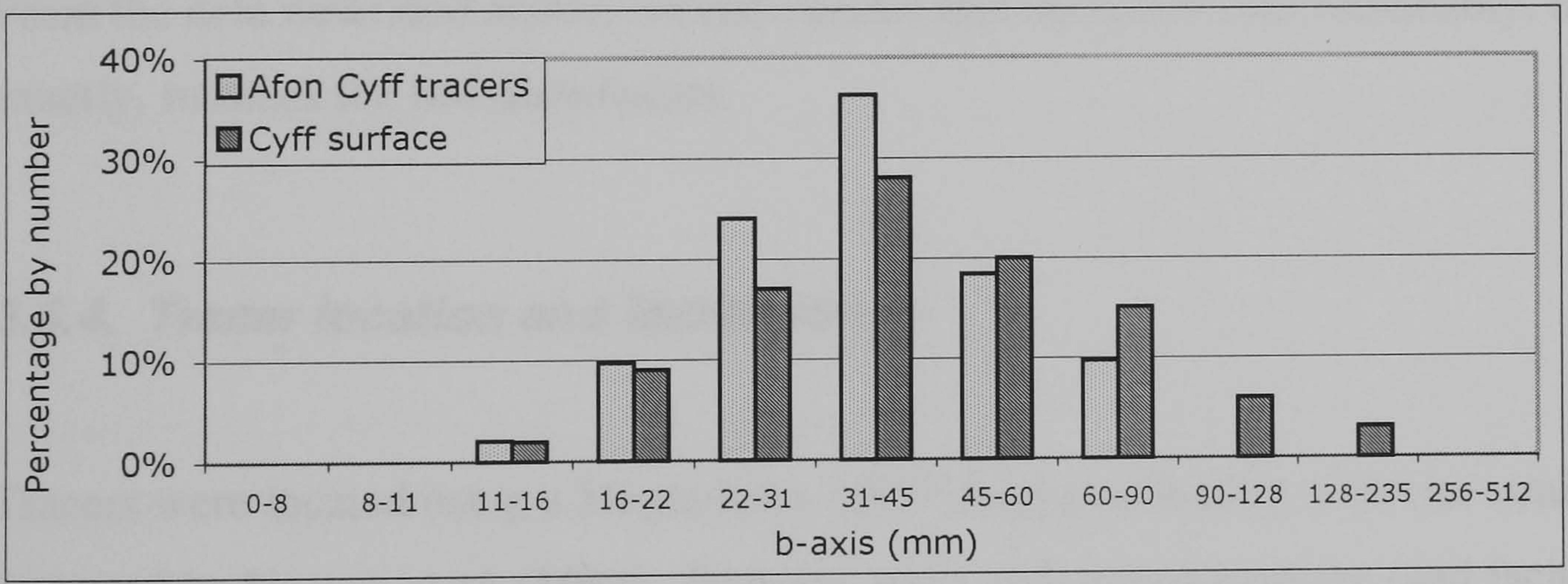


Figure 3.6. Tracer and surface size distributions for the Afon Cyff

The bed distribution is represented by 200 randomly sampled tracers from the surface of the Nant Tanllwyth at four exposed and semi-exposed sediment stores through the reach.

Figure 3.5 shows the tracer distribution in the Nant Tanllwyth to be comparable to previous surface counts in the channel. The coarser size distribution of tracers originally seeded in the Afon Cyff (Figure 3.6) reflects its coarser size distribution (see section 1.6.2).

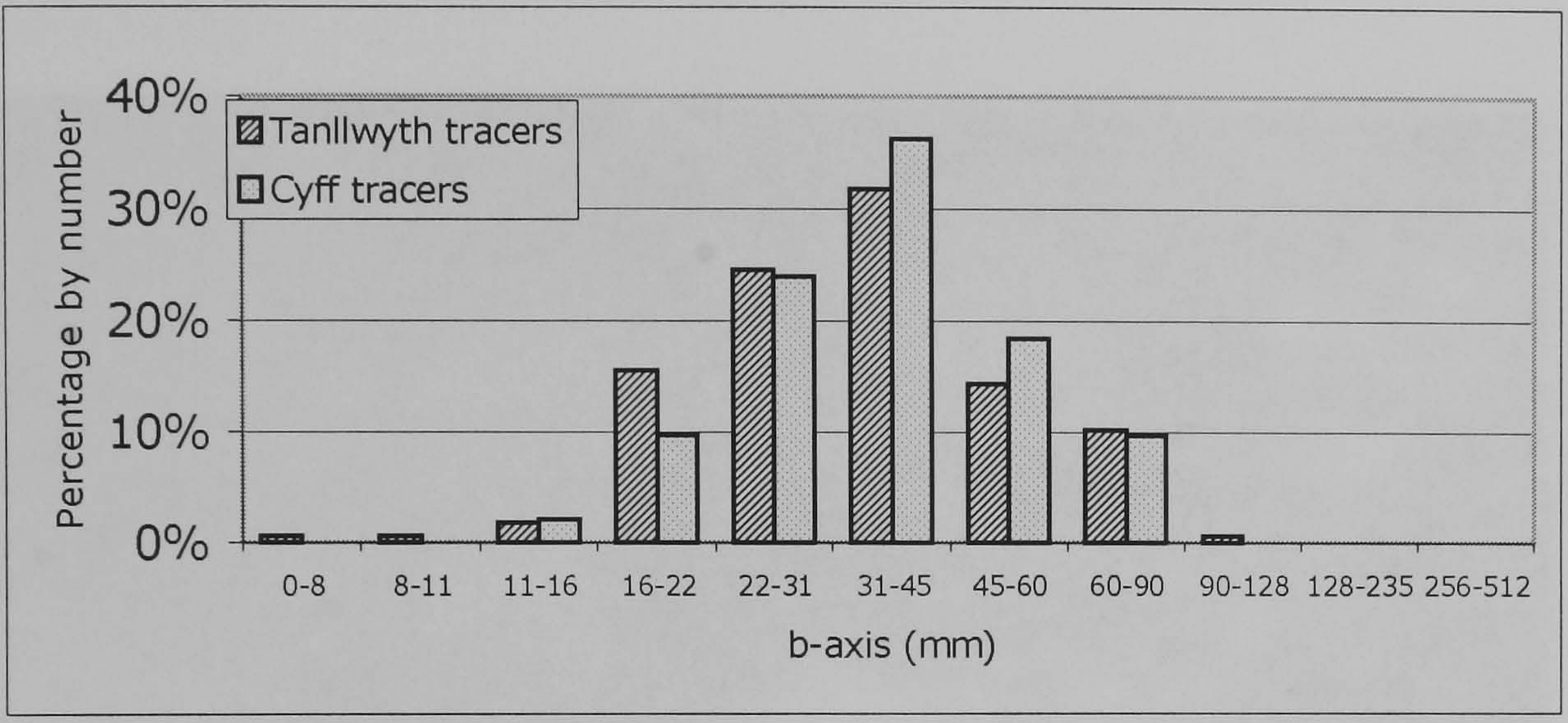


Figure 3.7. Tracers size distributions for Nant Tanllwyth and Afon Cyff

From the data described above, we can assume that the tracer data reasonably, but not exactly, matches the bed distribution.

3.5.4. Tracer location and identification

Tracers were located using a Magnotrack 100™ magnetic locator, a device similar to that used by Hassan *et al.* (1984). Searches were undertaken working (and facing) downstream, whilst standing (with non-ferrous footwear) on the bed of the channel. The detector was passed across the entire bed on a broad search setting to maximise search radius. When a signal was received from a ferrous or magnetic object, the sensitivity settings were reduced to exactly locate the found object. Search radius was approximately 0.5 m, with depth up to approximately 0.45 m. The waterproof detector could operate in water depths of up to 0.9 m. On location of the tracer, the searcher would dig the tracer from the bed and replace it with a temporary marker. The identity of the tracer would then be established, and its position recorded using the two-tape method. The searcher would stretch the tapes (see Plate 3.6) above the marked point and hold the detector vertically on the point on the bed at which the tracer was found. The tape readings at a point vertically above the tracer location would then be made. Recordings of local conditions, depth within sediment and depth of water were also made.

Plate 3.6. The two-tapes method. Tracer pebble location and mapping in the Nant Tanllwyth

The tracer was then replaced and reburied to its original depth and covered as well as possible with excavated sediment. This process was both technically difficult and time consuming. Theoretically to maintain the tracer's integrity as an undisturbed clast for further transport and account for particle clustering (Brayshaw *et al.*, 1983), one would have to exactly imbricate the tracer within its original matrix and to its exact depth. Although Drew (1992) claimed disturbance in his study to be minimal at these depths, this proved impossible in the field and with deep excavations of up to 0.4 m necessary, this was a source of error. How the effects of these disturbances and the different circumstances of the first trace on overall travel distances must be considered. The stream bed of the Nant Tanllwyth and Afon Cyff are both characterised by low sediment and water depths. Excepting the first test trace (where only 20 tracers moved slightly lower distances), examination of a particle's first movement in comparison with future movements of matching size classes and under similar flow magnitudes did not show any significant differences. It was felt therefore that to remove tracers from the dataset would not be appropriate. Search procedure was identical in both channels, though deeper water in general was found in the Afon Cyff whilst deeper sediments tended to characterise the Nant Tanllwyth.

Identification was made by recording the serial number within the small epoxy window on the clast. Serial numbers ran from 1-99, from A-Z, and from AA-GZ. On occasion, due to a broken tracer or damaged epoxy window, identification in the field was impossible. Two courses of action were possible:

1 The location of the tracer was recorded, its dimensions measured and the tracer was then removed from the experiment and scratch marked for identification, or

2 if there was only *uncertainty* as to the tracer identification, the epoxy window was dug out and the tracer label established. If possible, the tracer was then marked by scratching a label into the surface of the rock. These tracers were later removed from the abrasion study since their mass would have been artificially altered after scratching.

On return to the laboratory, any tracers not having positive identification were identified using the central database based upon their weight, size and location parameters. Tracers that could not be positively identified were stored until the study end, when further attempts to identify them were made by a process of elimination. Tracers were n

3.5.5. Analysis of tracer positions and travel distance.

Distances were computed based on distance moved from the seeding point, or last traced position to finish point. The two Cartesian co-ordinates were used to calculate the shortest path between the two points. Small error is associated with this where a tracer passes around a significant bend in the channel. However, within the Nant Tanllwyth only one such point existed. In the Afon Cyff, the channel was almost straight, and the amount of error was negligible. After experimentation with various macros to simulate following the thalweg, it was found that drawing straight vectors between points was in fact the most accurate method. The full discussion on travel distances and relative speed of movement is discussed in the results section 4.31.

3.6. Abrasion

Length measurements of a, b and c axes of each clast were made and mass recorded to 0.1 g. These were recorded both at the start of the study, before tracers were introduced into the channels and at the end of the study, when they were removed. Abrasion measures were taken on freely moving clasts only to represent as closely as possible the effects of travel distance, burial and time on the abrasion of individual clasts. A dataset of abrasion against hydrologic and travel distance parameters could be constructed.

3.7. Summary

This section has described the techniques of monitoring bedload by both tracing of individual clasts and trapping total bedload outputs. It demonstrates the improvements in the bedload-monitoring network since previous studies took place in the catchments. With the availability of new technology, this trapping network has been augmented further with the use of tracers to examine individual particle travel distances through the channels. The catchments are particularly well provided with hydrometric data and it is anticipated that the analysis of thresholds of these data can be used as a basis for examination of bedload flux.

Section 4: Results

4.1. Hydrological monitoring

Institute of Hydrology monitoring flumes (see section 3.1) were used to collect data from the Nant Tanllwyth and Afon Cyff catchments. Data are presented from the duration of fieldwork and are delimited into study-periods that correspond to field measurements. The aim of this section is twofold:

1 To define and describe the hydrological profile of the two catchments, and
2 to assess the degree to which the catchments can realistically be classed as paired.

The data will be examined at a range of scales. Firstly, for the duration of the field work. Secondly, split into each study period and thirdly, through yearly comparison with historical data.

4.1.1. Hydrological statistics: duration of fieldwork

This section will analyse the continuous flow data and the major hydrological features from the two experimental catchments. It will draw comparison between the Nant Tanllwyth and Afon Cyff and describe the main influences on the results that are presented.

The summary hydrological data for the Nant Tanllwyth and Afon Cyff catchments for the duration of fieldwork is shown in Table 4.1.

Table 4.1. Discharge characteristics for study period 16th January 1995 - 2nd June 1997.

	Stream discharge (m^3s^{-1})		
	Maximum	**Minimum**	**Mean**
Nant Tanllwyth.	2.316	0.045	0.051
Afon Cyff.	6.358	0.037	0.159

Table 4.1 shows mean and maximum stream discharge in the Afon Cyff to be greater than in the Nant Tanllwyth by factors of 2.74 and 3.10 respectively. Low flows, both minimum and analysed $Q_{0.95}$ flows (not shown) are relatively comparable. This is in direct relation to catchment areas, with the Afon Cyff 3.1 km^2 and the Nant Tanllwyth 0.89 km^2 (a factor of 3.5).

Figures 4.1 and 4.2 show the discharge from the complete 15-minute discharge record of both streams. The hydrograph is split into 6-month blocks, starting from the first fieldwork on 16th January 1995 and finishing on the 2nd June 1997. Felling in the Nant Tanllwyth is indicated by the vertical dashed line in Figure 4.1.

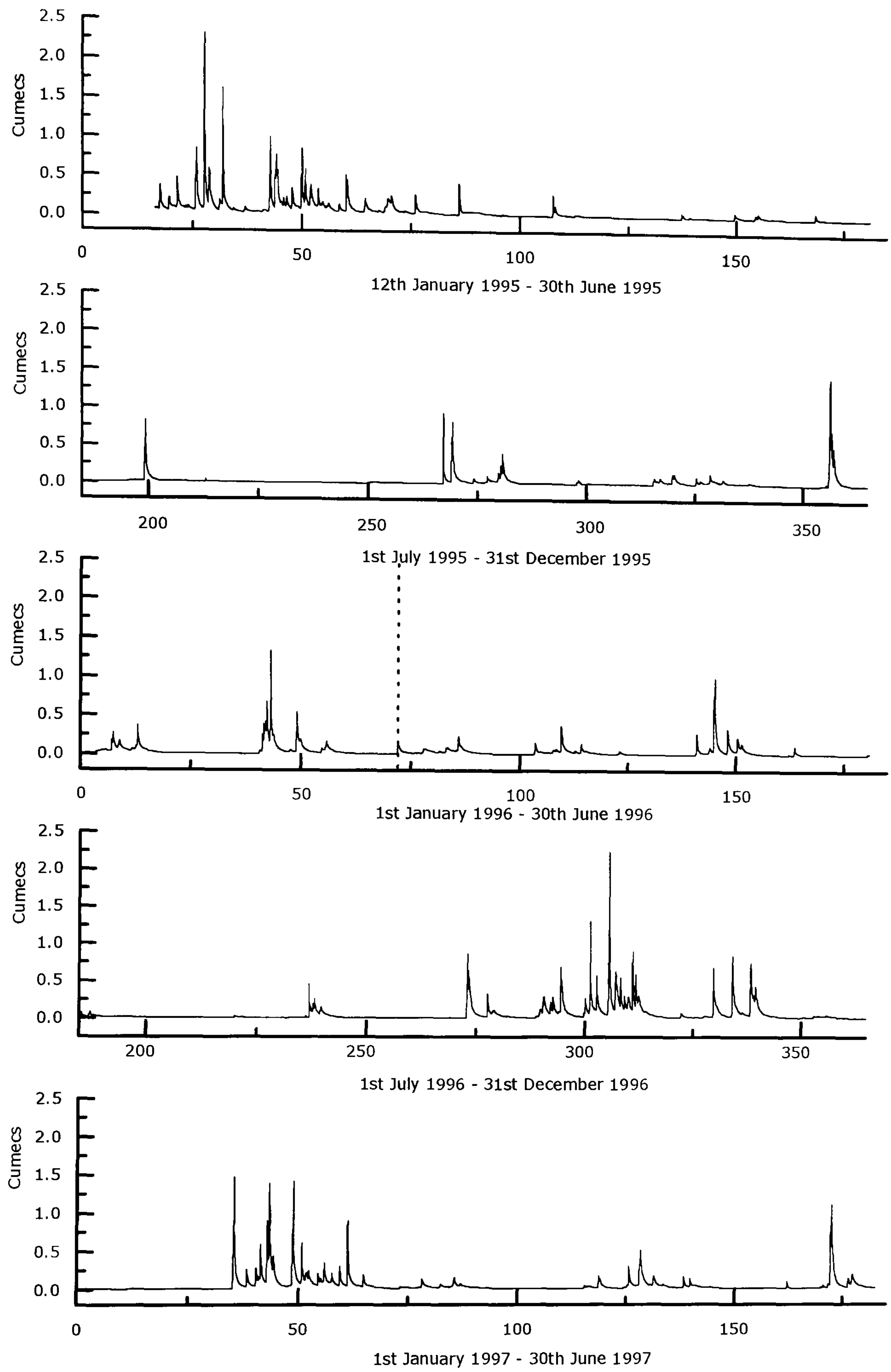


Figure 4.1. Time series graphs showing 15 min flow data for Nant Tanllwyth

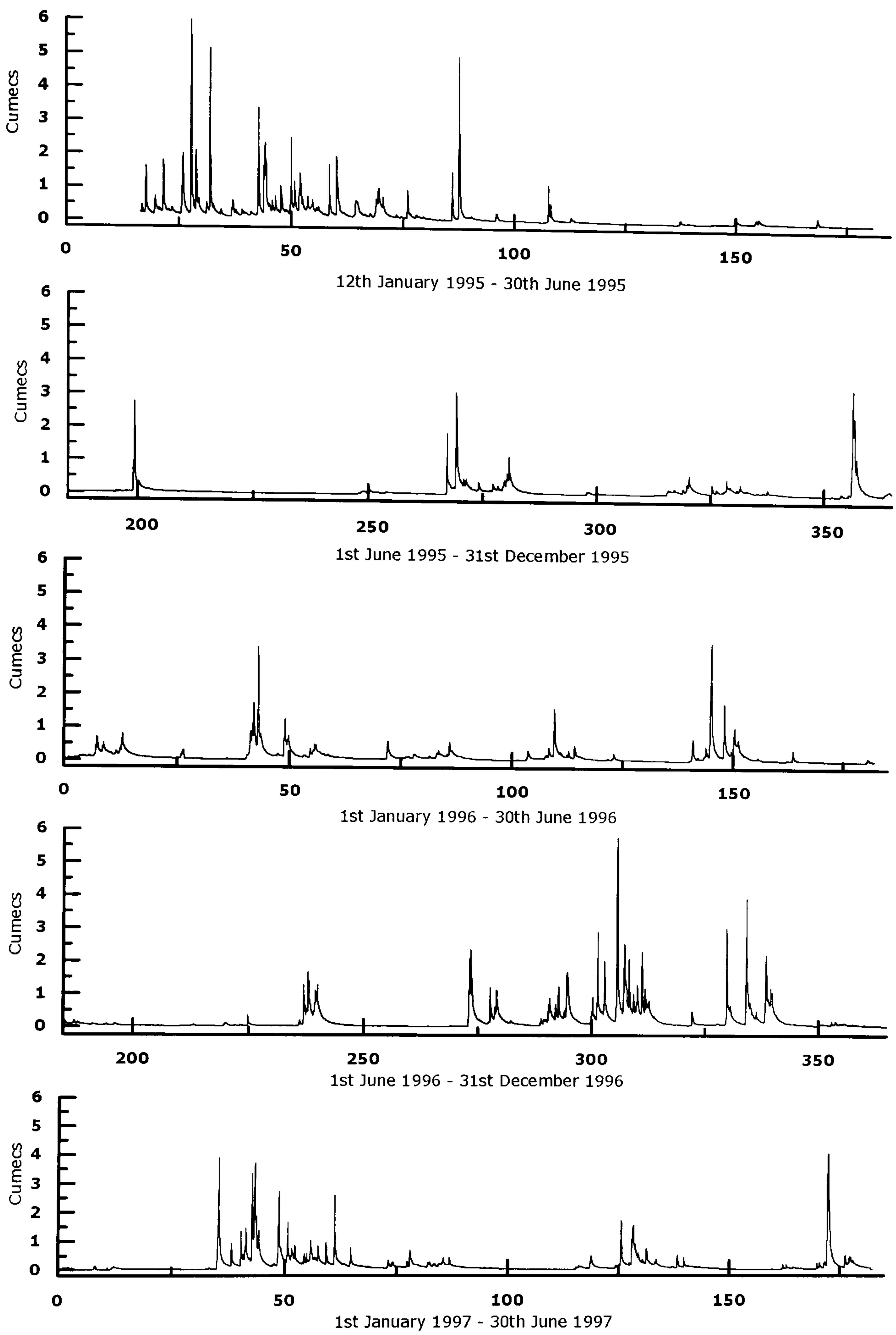


Figure 4.2. Time series graphs showing 15 min flow data for Afon Cyff

Note the difference in scales between graphs, with the Afon Cyff maximum set at 6 m^3s^{-1} and the Nant Tanllwyth maximum set at 2 m^3s^{-1}.

In contrasting and examining the long-term hydrographs of the two catchments, it is possible to use these data as a sound basis for comparison of bedload fluxes and dynamics in later sections. The competent flow thresholds and hydrograph behaviour will be an important control on the bedload transport parameters being studied. We can examine the base-data of the two catchments in several ways.

Flood magnitude is consistently and reliably greater in the Afon Cyff. Any flows in the Nant Tanllwyth above baseflow are mirrored in the Afon Cyff by a factor of approximately three. A relationship of $y = 2.94\ x + 0.0013$, $r^2 = 0.94$ exists for exact 15 minute timings; using averaged hourly data significantly improves this relationship approaching $r^2 = 1$. The total catchment areas of the Nant Tanllwyth (0.89 km^2) and Afon Cyff (3.1 km^2) mean that the Nant Tanllwyth is 29% of the size of the Afon Cyff, whereas flow magnitudes are on average 34% of the Afon Cyff.

Flood response timing has been analysed and both the Nant Tanllwyth and Afon Cyff respond similarly. Flood peaks are attained in both catchments within 45 minutes of each other (and in most cases are at identical times), except for on one occasion (see below). Previous work in forested catchments has shown a delay in flood peaks under heavy plantation due to precipitation interception and delayed transport to stream pathways. In the case of the Nant Tanllwyth however, it is suggested that these factors are offset by the effect of drainage ditches within the catchment, which give rise to rapid runoff throughout the artificial drainage network.

Both catchments exhibit long periods of low flows, with the Nant Tanllwyth summer low flow being ~ 0.03 m^3s^{-1} and the Afon Cyff summer low flow being ~ 0.06 m^3s^{-1}. Despite the difference between these figures, evidence suggests that lengthy periods of low flows do not influence sediment transport (Shields, 1936) or the stability of the bedload matrix, as they are unable to promote even the movement of fines.

Figures 4.1 and 4.2 show 15 minute flood hydrographs for the entire study period, split into 6 monthly blocks. When the Nant Tanllwyth and Afon Cyff are overlain and compared, the only significant event within one channel not to have a duplicate in the other was on 28th March 1996 (day 87 of the study) in the Afon Cyff. This flow peak reached a magnitude of 4.95 m^3s^{-1}, whilst over the same period, no equivalent rise in the flow hydrograph was seen in the Nant Tanllwyth. This does not affect the transport measurements in the Afon Cyff as the channel was not monitored at that time.

Figures 4.1 and 4.2 demonstrate the exceedingly flashy hydrographs of both channels. Runoff from the shales and steep slopes is rapid, with drainage pathways assisting rapid transit of water through the fluvial system returning quickly to baseflow. A typical hydrograph is shown below in Figure 4.3. This shows a typical flood over a 24-hour flood period, with both rapid rise and fall of the hydrograph.

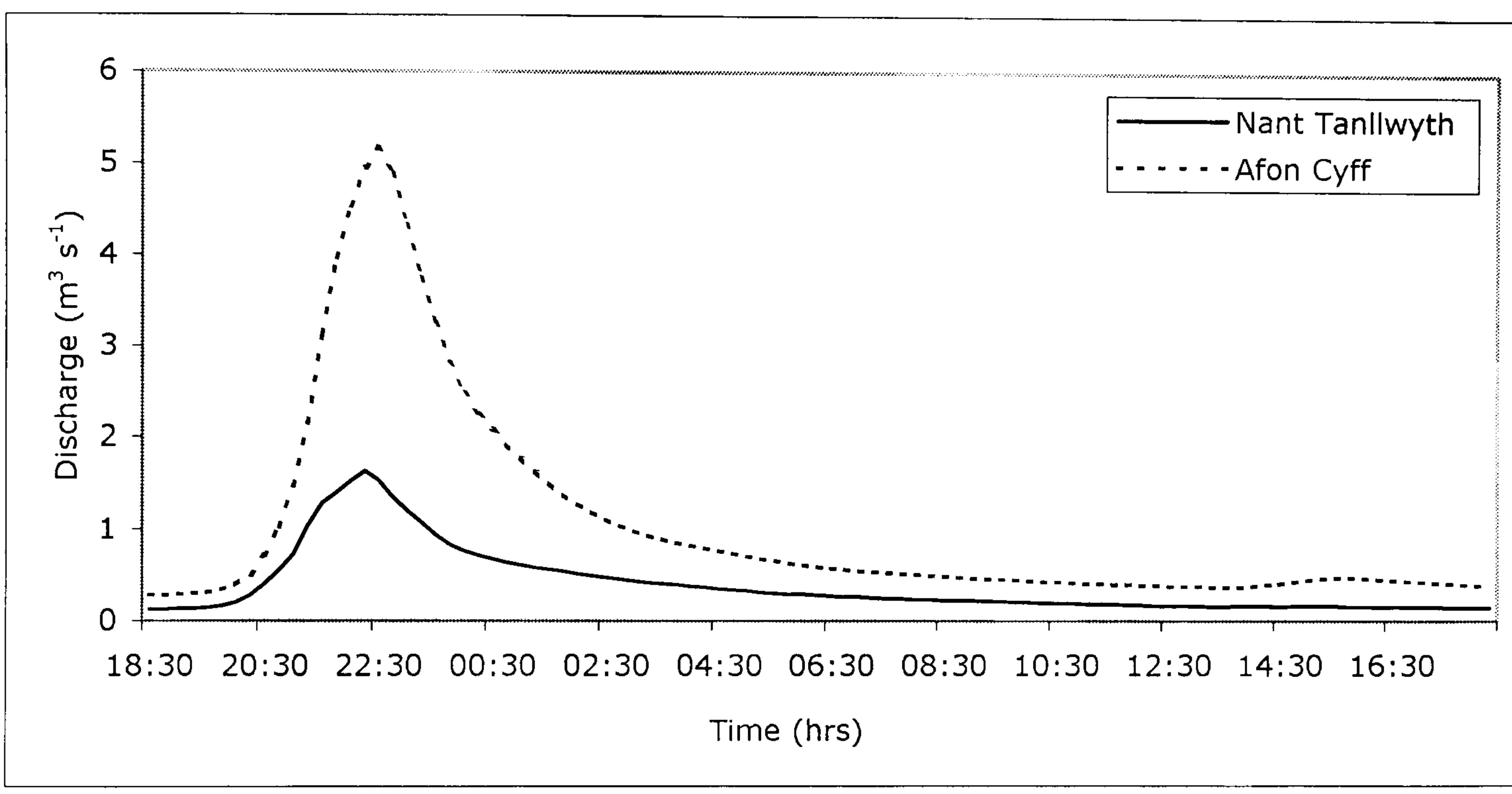


Figure 4.3. Example of a 24 hour flood hydrograph showing the Nant Tanllwyth and Afon Cyff on 1st - 2nd February 1995

4.1.2. Hydrological statistics: analysis by study periods

The practical implications of working in a fluvial environment, where fieldwork is largely event driven, meant that fieldwork intervals were not of fixed length. This was further emphasised by logistical and monetary constraints. As such, each visit to the field sites was dated and periods between these dates labelled as shown below. All further analysis refers to these dates and labels, which hereafter become known as the *study periods*. The complete time of study will be called the *duration of fieldwork* and the pre-harvest and post-harvest times referred to as *phases*. Table 4.2 shows the hydrological characteristics of the study periods, as well as their start and end dates.

Table 4.2. Flow characteristics for the duration of fieldwork, split into study periods

			Nant Tanllwyth		Afon Cyff	
Period name	**Period dates**	**Up to Julian day**	**Mean (m^3s^{-1})**	**Maximum (m^3s^{-1})**	**Mean (m^3s^{-1})**	**Maximum (m^3s^{-1})**
A	16-Jan-95 to 03-Feb-95	**18**	0.18	2.32	0.49	6.36
B	03-Feb-95 to 15-Mar-95	**58**	0.12	1.00	0.37	3.40
C	15-Mar-95 to 24-May 95	**128**	0.03	0.41	0.09	4.97
D	24-May 95 to 07-Jul-95	**172**	0.02	0.09	0.06	0.54
E	07-Jul-95 to 27-Jul-95	**192**	0.03	0.81	0.08	2.75
F	27-Jul-95 to 11-Aug-95	**207**	0.01	0.04	0.02	0.04
G	11-Aug-95 to 05-Oct-95	**262**	0.02	0.93	0.09	3.09
H	05-Oct-95 to 15-Oct-95	**272**	0.06	0.41	0.20	1.16
HA	15-Oct-95 to 26-Oct-95	**283**	0.02	0.06	0.05	0.14
I	26-Oct-95 to 15-Dec-95	**333**	0.03	0.16	0.11	0.64
J	15-Dec-95 to 11-Jan-96	**360**	0.07	1.43	0.20	3.28
K	11-Jan-96 to 18-Jan-96	**367**	0.06	0.37	0.20	0.79
KA	18-Jan-96 to 20-Feb-96	**400**	0.06	1.33	0.17	3.40
L	20-Feb-96 to 26-Mar-96	**435**	0.04	0.25	0.13	0.60
M	26-Mar-96 to 02-Apr-96	**442**	0.04	0.12	0.12	0.30
MA	02-Apr-96 to 03-May-96	**473**	0.04	0.38	0.12	1.60
N	03-May-96 to 02-Jul-96	**533**	0.04	0.99	0.12	3.56
O	02-Jul-96 to 01-Oct-96	**624**	0.03	0.88	0.09	2.34
P	01-Oct-96 to 19-Nov-96	**673**	0.12	2.25	0.37	5.78
Q	19-Nov-96 to 10-Dec-96	**694**	0.10	0.84	0.35	3.91
R	10-Dec-96 to 14-Mar-97	**788**	0.07	1.48	0.20	3.90
S	14-Mar-97 to 09-Apr-97	**814**	0.03	0.16	0.13	0.68
T	09-Apr-97 to 02-Jun-97	**868**	0.04	0.52	0.12	1.72
Overall duration of fieldwork			**0.05**	**2.32**	**0.17**	**6.36**

The pertinent data in Table 4.2 above is summarised graphically below, in Figures 4.4 - 4.5. The horizontal line in Table 4.2 delimits the pre- and post-harvesting phases.

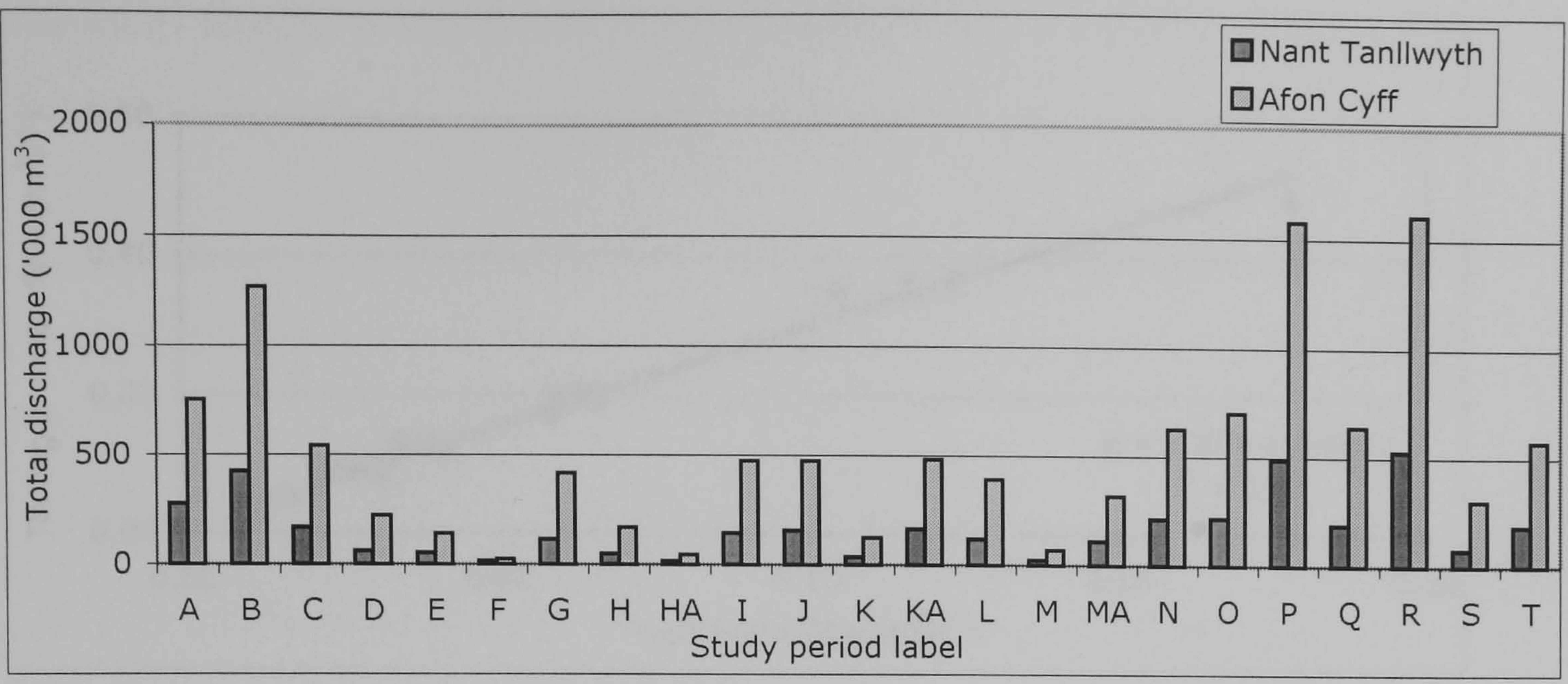


Figure 4.4. Total streamflow in the Nant Tanllwyth and Afon Cyff during delimited study periods

The variation in terms of both magnitude and seasonality of flow regimes of the Nant Tanllwyth and Afon Cyff is demonstrated in Figure 4.4. Seasonal differences are noticeable, with all the wettest periods B, P and R falling within winter months. Figure 4.4 also highlights the range of flow regimes experienced between fieldwork events, with significant variation around the high winter discharge periods. This is typical of a wet maritime climate such as that experienced on Plynlimon. Note that the histogram delimits periods of variable lengths.

Figure 4.5 shows the relationship between the Nant Tanllwyth and Afon Cyff in terms of catchment means through each study period.

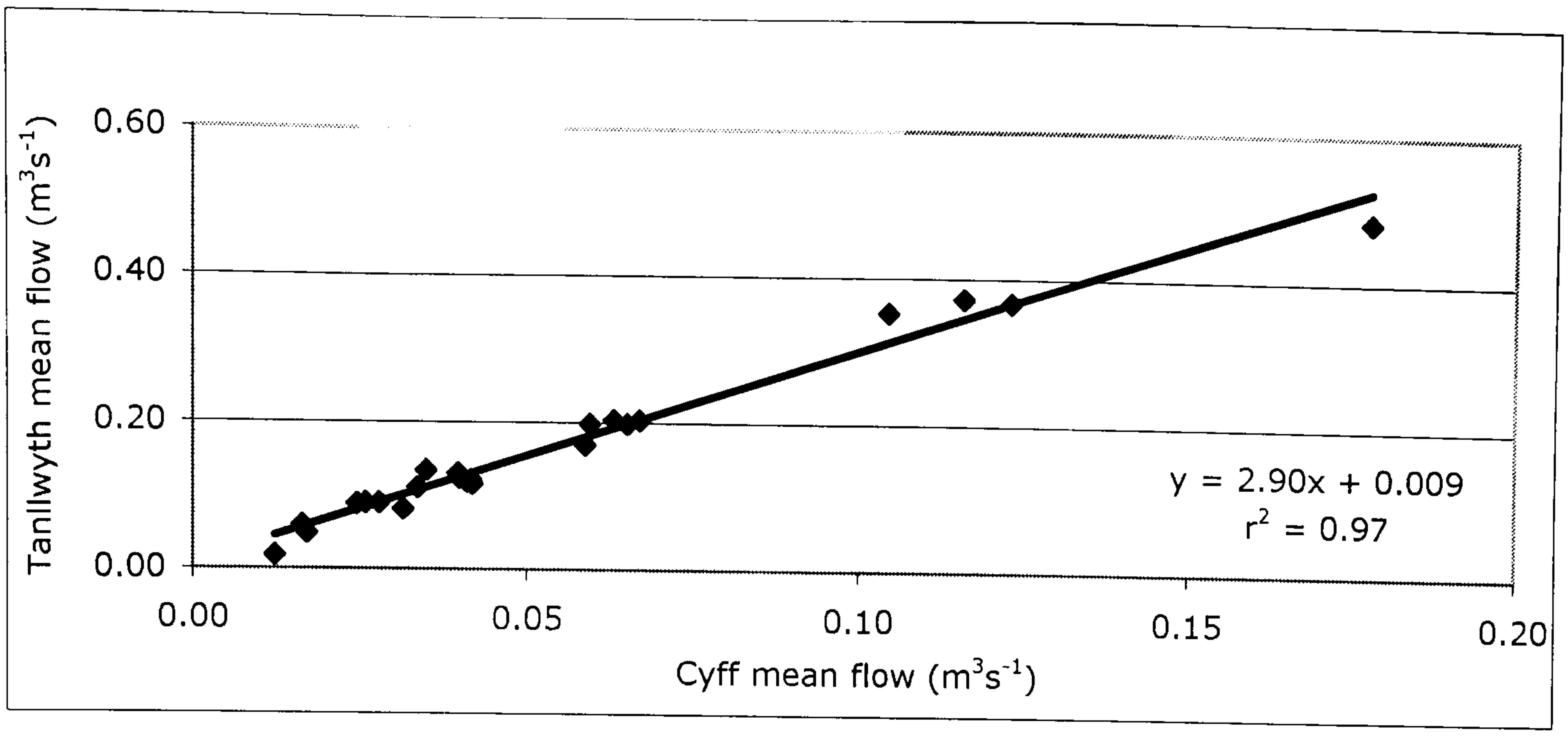


Figure 4.5. Graphical comparison of catchment discharge means in the study periods

Figure 4.6 shows the relationship between the Nant Tanllwyth and Afon Cyff in terms of catchment maxima through each study period.

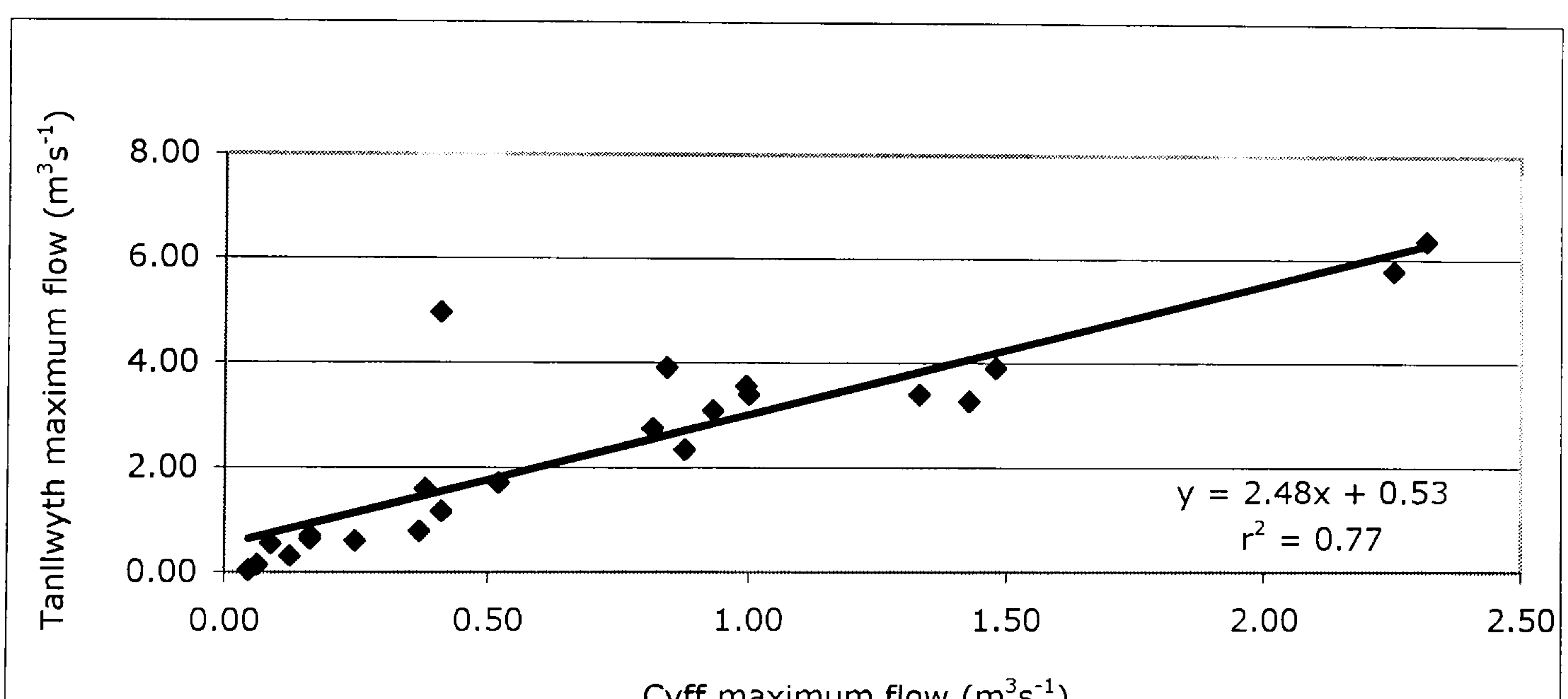


Figure 4.6. Graphical comparison of catchment maximum discharges in the study periods

Figures 4.5 and 4.6 above show significant correlation in mean flows through study periods, though a reduced significance in correlation between maximum events in the channels. Hydrologically therefore, the maximum and mean hydrologic responses of the catchments can be considered paired. However, the flood peak of 28th March 1996 in the Afon Cyff did not affect the Nant Tanllwyth. This point does not affect the analysis of bedload or tracer data, as the Afon Cyff monitoring programme had not been initiated during period C.

All of these graphs go to illustrate the variety in flow regime through the study period, and highlight the implications for studying bedload transport in these fluctuating conditions.

4.1.3. Nant Tanllwyth: pre-harvest and post-harvest hydrology

One advantage of the paired catchment approach is in the ability to maintain a constant reference in a case of changing land use (Ferguson *et al.*, 1991). However, when examining any time series experiment, the changing base parameters, in this case flow, will affect the overall experiment. With the date of land use change defined as April 2nd 1996, flow in the pre-harvesting and post-harvesting phases must be examined. The onset of harvesting was earlier than this, falling in mid March, with harvesting completed in early May. April 2nd has been chosen as the date to define the boundary of the two phases. It conveniently delimits two flow monitoring periods and it is in the middle of the short harvesting period when there were only low flows (Figure 4.1) in the Nant Tanllwyth. Comparison of two separate phases is extraordinarily difficult. The periods are shown in Table 4.3 below.

Table 4.3. Definition of pre- and post- harvest phases and summary hydrologic data

	Pre-harvest	**Post-harvest**
Start date - End date	**16th January 1995 - 2nd April 1996**	**2nd April 1996 - 2nd June 1997**
Period length (days)	442	426
Total Discharge ('000 m^3)	1840	2020
Mean flow m^3s^{-1}	0.048	0.055
Maximum flow m^3s^{-1}	2.32	2.25
Number of peaks above 0.3 m^3s^{-1}	26	25
Number of peaks above 0.5 m^3s^{-1}	16	21
Number of peaks above 1 m^3s^{-1}	5	7

Table 4.3 demonstrates firstly that the pre-harvest and post-harvest phases are comparable in length and exhibit comparable flow characteristics. Subtle differences in the data are, however, shown. The total discharge and therefore the mean discharge, is 17% greater in the post-harvesting phase than in pre-harvesting phase. More importantly for bedload entrainment however, is that the pre-harvest phase, although having a slightly higher maximum has a smaller number of flood peaks in the above 0.5 m^3s^{-1} threshold. The differences are not marked, but examination of the long term hydrographs in Figures 4.1 also shows the Nant Tanllwyth flow peaks exhibit clustering in the first 60 days of the pre-harvesting phase. In the post-harvest phase, peaks are more widely distributed though a seasonal distribution is still evident. Analysis was made of both peak and mean flow in pre- and post harvest phases comparing with the Afon Cyff. Mean flow in the Nant Tanllwyth was showed a slight decrease compared to the Afon Cyff, though peak flows showed a slight decrease. The differences in the data were subtle could not be relied upon as the basis for assuming changes in hydrology. With any short to medium term project comparing two phases, there is a difficulty in ensuring a seasonal balance within the data. The problem can arise in two ways: firstly, the time phases are not precisely matched in terms of seasonal start and end dates. Secondly, one of the phases might incorporate an extreme hydrometric period, with unseasonable high or low flows. The project attempts throughout to make dimensionless units of travel distances and bedload yields, but a short summary of the study phases compared to each other and to previous years' data is given below.

4.1.4. Examination of historical data

For the Nant Tanllwyth and Afon Cyff, historical hydrological data were made available by the Institute of Hydrology. Tables 4.4 and 4.5 below summarise the flow during the previous 22 years. This flow period covered the period use by Moore and Newson (1986) in their study, and provided a long-term record. Although it is difficult to impose artificial time boundaries on geomorphological data, it is essential, nevertheless, to test for completeness the comparability of the years studied to previous records. To eliminate error and compare similar data, only years 1995 and 1996 are presented, a full record of 1997 was not available, and combining results may bias an examination due to seasonality of flow.

Table 4.4. Historical flow records of the Nant Tanllwyth catchment

Year	Maximum m^3s^{-1}	Mean m^3s^{-1}
1973	2.366	0.079
1974	2.111	0.068
1975	2.106	0.046
1976	1.717	0.037
1977	5.464	0.060
1978	1.671	0.054
1979	2.382	0.062
1980	2.373	0.060
1981	2.244	0.066
1982	1.859	0.059
1983	2.152	0.065
1984	1.515	0.052
1985	1.858	0.062
1986	2.334	0.073
1987	2.294	0.062
1988	2.419	0.068
1989	2.656	0.093
1990	1.873	0.061
1991	2.511	0.060
1992	2.396	0.067
1993	2.141	0.066
1994	2.460	0.086
Mean	**2.314**	**0.064**
1995	***2.315***	***0.051***
1996	***2.251***	***0.051***

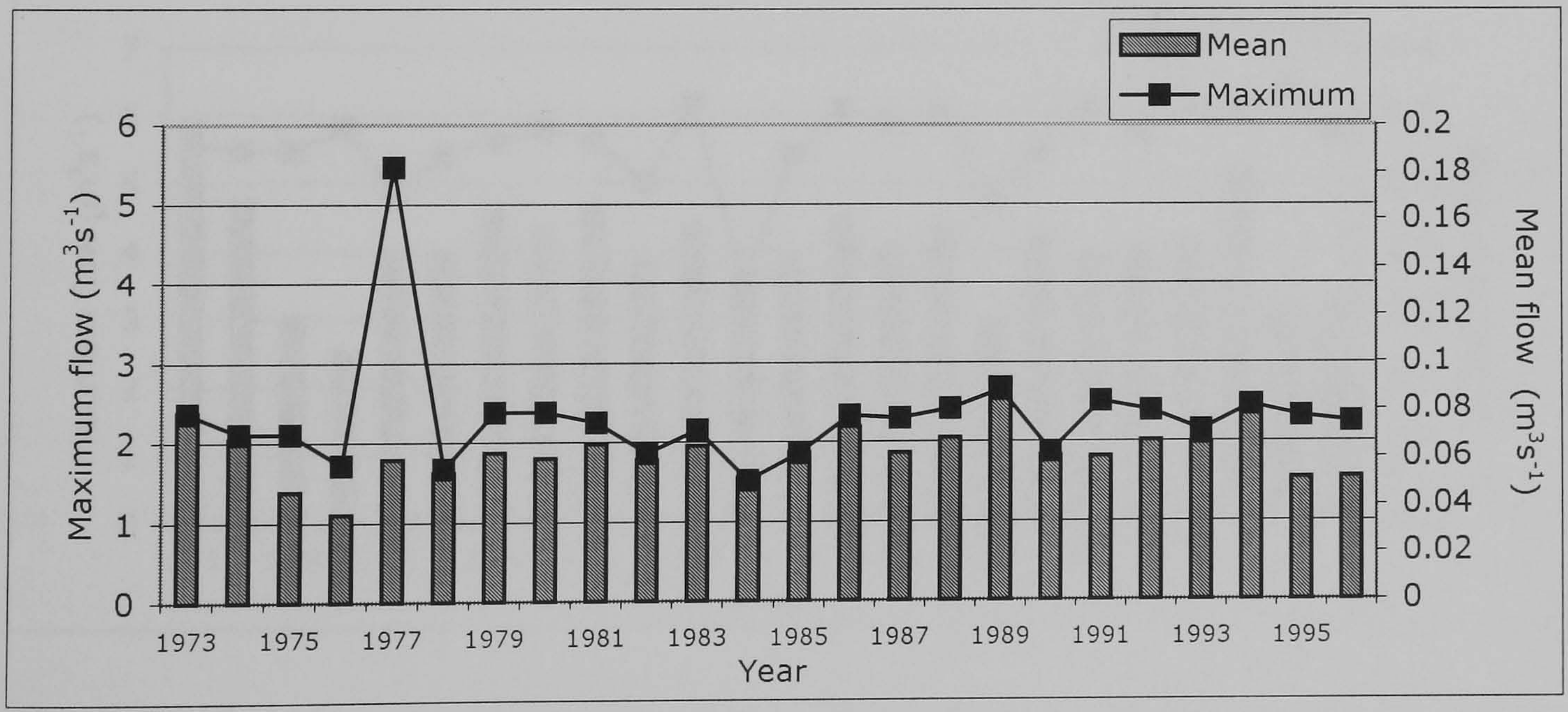


Figure 4.7. Comparison of Nant Tanllwyth archive data and fieldwork duration data

Table 4.5. Historical Flow Characteristics of the Afon Cyff Catchment

Year	MAX	AVG
1973	5.572	0.296
1974	5.504	0.238
1975	5.470	0.152
1976	5.812	0.126
1977	4.856	0.201
1978	5.422	0.199
1979	5.638	0.235
1980	5.788	0.217
1981	5.686	0.233
1982	5.003	0.191
1983	6.174	0.220
1984	3.538	0.169
1985	5.450	0.196
1986	6.065	0.225
1987	5.911	0.202
1988	6.041	0.218
1989	4.767	0.147
1990	5.511	0.213
1991	6.082	0.196
1992	5.764	0.201
1993	6.160	0.207
1994	6.083	0.262
MEAN	**5.559**	**0.207**
1995	***6.358***	***0.157***
1996	***5.778***	***0.165***

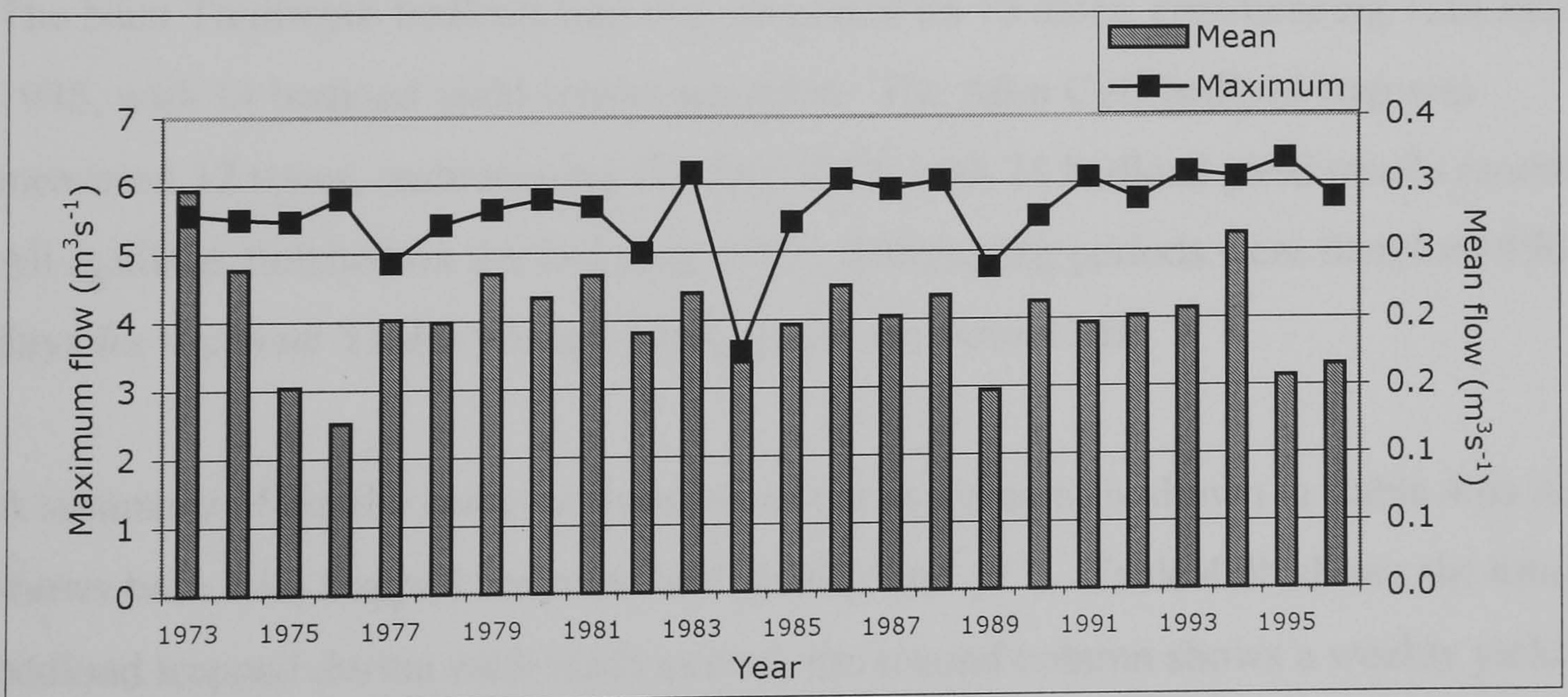


Figure 4.8. Comparison of Afon Cyff archive data and fieldwork duration data

Table 4.4 illustrates that the mean of the archive data in the Nant Tanllwyth was higher than the two years analysed over the duration of fieldwork. Although maximum flows are slightly higher, these figures illustrate peak events and without a complete distribution, it is not possible to interpret these maxima as a trend. Similar observations are also available in the Afon Cyff (Table 4.5, Figure 4.8) retaining high flow peaks with a notably lower mean. In conclusion, years 1995 and 1996 are seen overall, to show lower discharge, but retain similar peak flows.

4.2. Coarse sediment trapping

Bedload traps located at the downstream end of each experimental channel were dipped to determine total bedload yields from the channel (see section 3.4). Data were related to total duration of fieldwork, to individual study periods and to the pre- and post-harvest phases in the Nant Tanllwyth. Within these constraints, data were related to a number of chosen discharge thresholds.

4.2.1. Initial data presentation

The Nant Tanllwyth bedload trap was measured on 15 dates, commencing 12th January 1995, with 14 bedload yield results recorded. The Afon Cyff bedload trap was measured 12 times, commencing 7th July 1995, with 11 bedload yield results recorded. All readings finished on the 2nd June 1997. Monitoring periods were therefore 850 days for the Nant Tanllwyth and 696 days for the Afon Cyff.

A summary of results from the duration of the experiment is shown in Table 4.6a and shows both total trapped sediment and yield (t km^2 yr^{-1}). Table 4.6b shows the total bedload trapped during each study period, the second column shows a weekly yield for each of the study periods and illustrates the variation in bedload discharge between study periods.

Timing of bedload trap dips was constrained by the availability of equipment, vehicles and assistant personnel and thus the dip intervals do not always correspond during the early study periods for each river. Furthermore, construction of the dipping devices on the Afon Cyff bedload trap was not completed until 7th July 1995. All calculations, however, are based upon the period lengths for each river, and further analysis of bedload flux based on flow and time parameters always take the real time, or flow between dips into account. Table 4.6a below shows the yields of the Nant Tanllwyth and Afon Cyff over the complete duration of fieldwork.

Table 4.6a. Bedload yields for the Nant Tanllwyth and Afon Cyff for fieldwork duration

	Study length (yrs)	Catchment area (km^2)	Total output (t)	Yield t km^{-2} yr^{-1}
Nant Tanllwyth	2.3	0.89	18.09	8.68
Afon Cyff	1.9	3.13	5.40	0.91

Table 4.6a shows more than a nine-fold difference in sediment yields between the Nant Tanllwyth and Afon Cyff. There is a significant difference between the outputs of the two channels. Table 4.6b summarises all of the monitoring periods undertaken in the Nant Tanllwyth and Afon Cyff. Dashes in cells below indicate no reading was made, thus cells with values indicate bedload accumulation since the previous reading. The grey hatched area shows the post-harvest phase of the Nant Tanllwyth.

Table 4.6b. Total bedload outputs of the Nant Tanllwyth and Afon Cyff measured using bedload traps

Period Names		Period Dates	Nant Tanllwyth		Afon Cyff.	
Specific periods for each river			Bedload output	Weekly yield	Bedload output	Weekly yield
Nant Tanllwyth	Afon Cyff		t	t wk^{-1}	t	t wk^{-1}
A-C	**A-C**	03-Feb-95 to 07-Jul-95	5.34	0.243	-	-
D	**D**	07-Jul-95 to 27-Jul-95	0.25	0.089	-	-
E-F		27-Jul-95 to 5-Oct-95	0.24	0.024	-	-
	D-G	07-Jul-95 to 15-Oct-95			0.76	0.053
H-I		5-Oct-95 to 15-Dec-95	0.03	0.003	-	-
	Ha-J	15-Oct-95 to 11-Jan-96	-	-	0.10	0.008
I-J		15-Dec-95 to 11-Jan-96	1.12	0.289	-	-
J-Ka	**J-Ka**	11-Jan-96 to 20-Feb-96	0.76	0.133	0.29	0.050
	Ka-M	20-Feb-96 to 02-Apr-96	-	-	0.23	0.039
Ka-Ma		20-Feb-96 to 03-May-96	0.07	0.006	-	-
	M-N	02-Apr-96 to 02-Jul-96	-	-	0.40	0.031
Ma-N		03-May-96 to 02-Jul-96	0.88	0.103	-	-
O	**O**	02-Jul-96 to 01-Oct-96	0.37	0.029	0.13	0.010
P	**P**	01-Oct-96 to 19-Nov-96	4.28	0.611	2.28	0.326
Q	**Q**	19-Nov-96 to 10-Dec-96	0.32	0.107	0.35	0.117
R	**R**	10-Dec-96 to 14-Mar-97	4.30	0.320	0.81	0.060
S	**S**	14-Mar-97 to 9-Apr-97	0.04	0.010	0.05	0.015
T	**T**	09-Apr-97 to 02-Jun-97	0.10	0.013	0.07	0.009
Totals:						
A-T		**03-Feb-95 to 02-Jun-97**	**18.09**	**0.149**	**-**	**-**
	D-T	**07-Jul-95 to 02-Jun-97**	**-**	**-**	**5.40**	**0.054**

Figure 4.9 and 4.10 show the study periods and illustrate the weekly bedload yield in the traps. Bedload output data are shown on the same scale for both the Nant Tanllwyth and Afon Cyff (note difference in discharge and bedload scales).

The maximum weekly value of 0.61 t wk^{-1} in the Nant Tanllwyth occurs between 1st October 1996 and 19th November 1996. During several other study periods, notably at the start of the fieldwork, in periods A - C, and during the two winter periods of 95/96 and 96/97 bedload totals are high and clearly relate to flood magnitudes in the Nant Tanllwyth. In contrast, Figure 4.10 shows that the Afon Cyff has yielded significantly lower totals, despite a catchment 3 times greater than that of the Nant Tanllwyth and flows of matching and greater magnitude. From a visual examination of the Afon Cyff data, it is possible to see from the bar charts a response to flood peaks, but the relationship is significantly less well defined than in the Nant Tanllwyth.

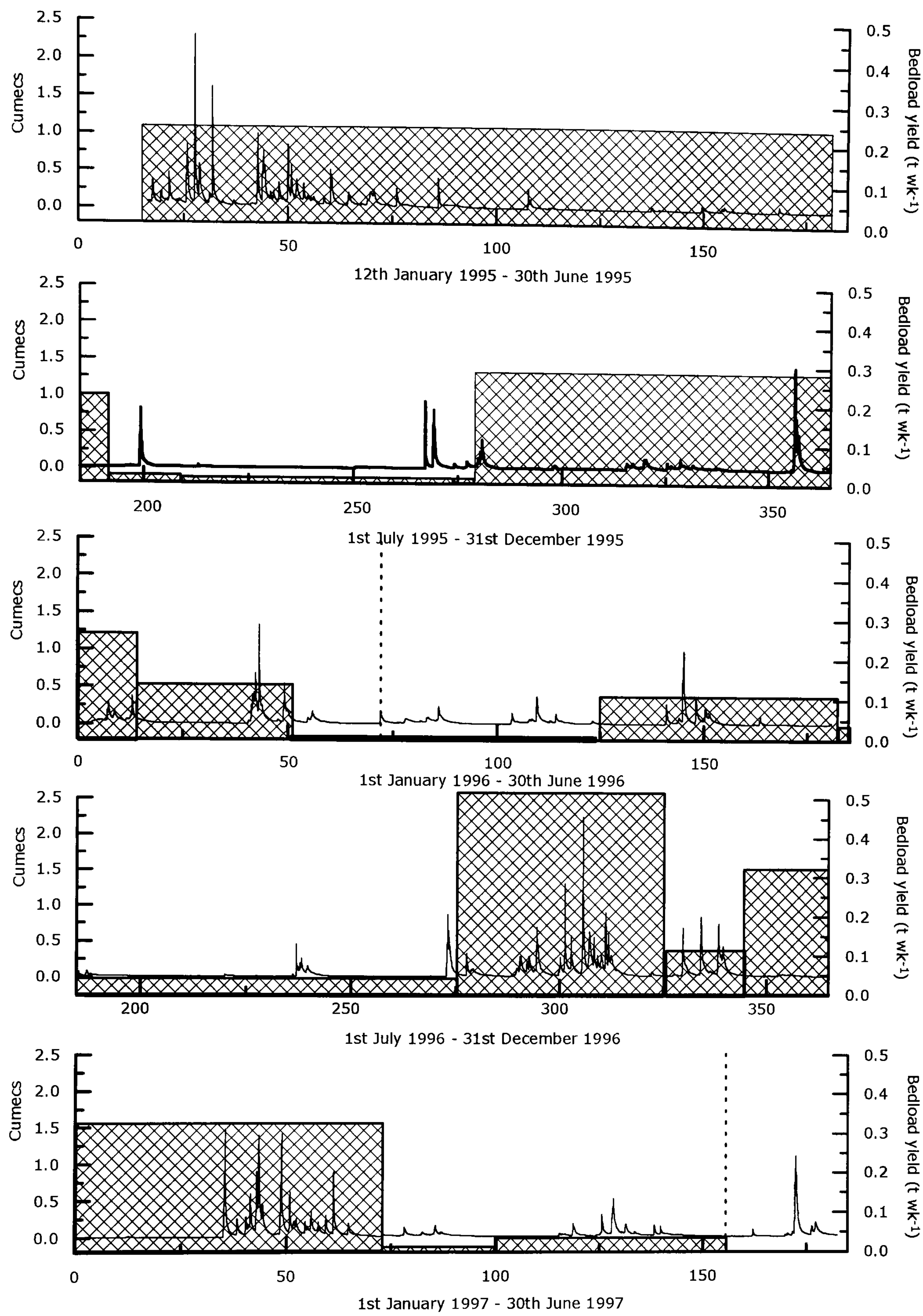


Figure 4.9. Bar charts showing bedload outputs and stream discharge in Nant Tanllwyth

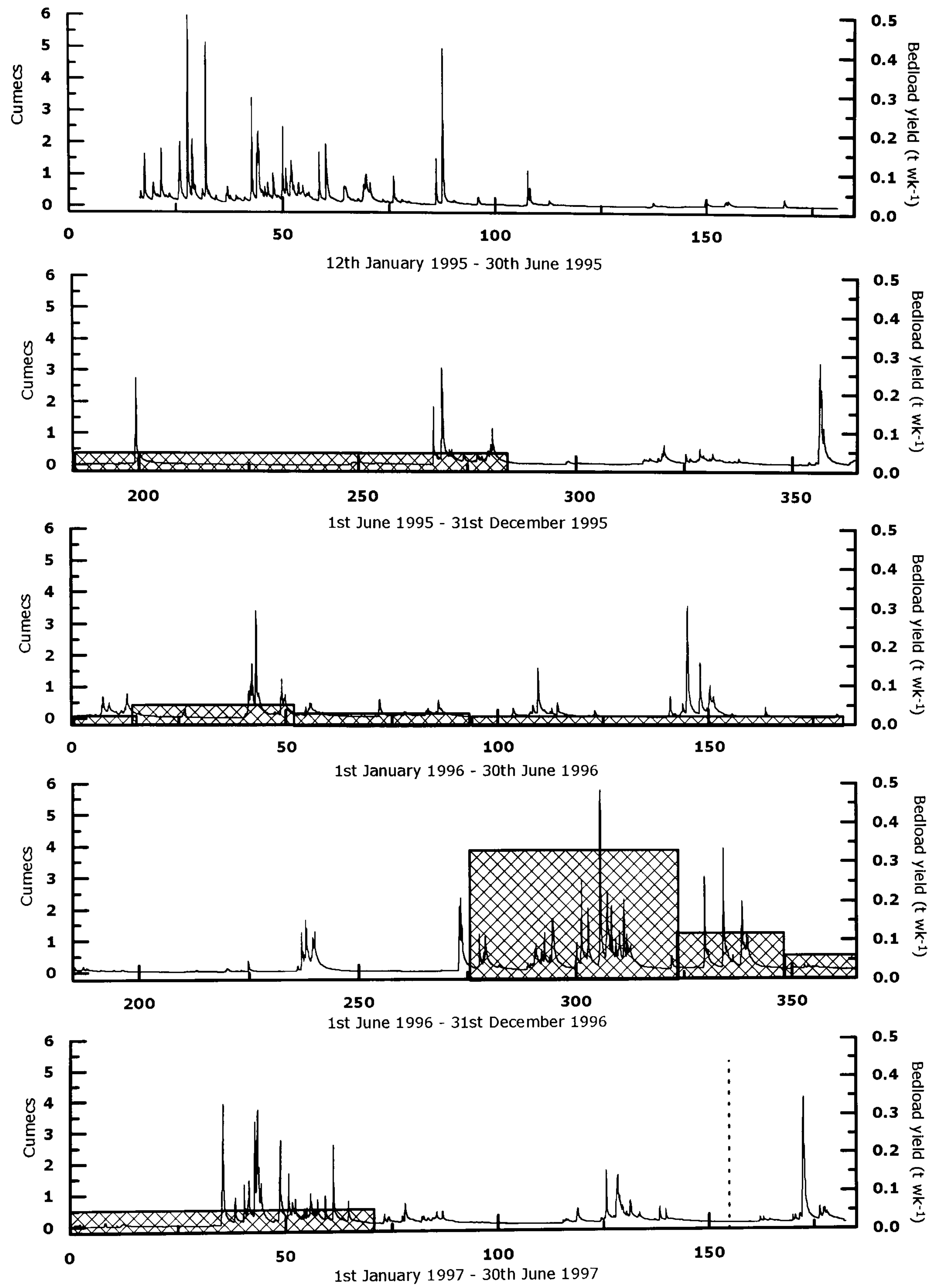


Figure 4.10. Bar charts showing bedload outputs and stream discharge in Afon Cyff

4.2.2. Analysis of bedload trap data

To attempt to approximate the relationship between channel discharge and total bedload output, a number of testing parameters were established. The channels were analysed using the flow thresholds in section 4.1, as long term field observations (Leeks, Marks, pers comm) had estimated floods of magnitudes 0.3 m^3s^{-1} and 0.5 m^3s^{-1} to be capable of initiating bedload movement. It was instructive initially to relate total bedload output to a function of time, followed by total discharge and subsequently to develop the parameters into a more detailed analysis of the flow distribution.

When correlating discharge threshold parameters with bedload yields, both a *time over a threshold* function and *total volume of flow over threshold* function were used. When relating flow parameters to bedload fluxes (tracers and traps) the *total flow over the discharge* gave consistently better results and r^2 values than a time over threshold function. Moore and Newson (1986) undertook multiple regression in the same channels and found that instantaneous discharge showed the best correlation; in this study this was not the case. These are subsequently referred to throughout the thesis. Total volume of flow over threshold is likely to be a better indicator and therefore exert greater influence on bedload transport parameters. It reflects not only duration of flow over threshold, but indicates the size of flood peaks within the time over threshold and therefore is a better measure of stream power (Sawyer *et al.*, 1996).

Relationships were constructed using higher discharge thresholds, but closest approximations were gained using the 0.5 m^3s^{-1} and 0.3 m^3s^{-1} thresholds. In addition, fewer periods were available for relating to floods of high magnitudes. In the Afon Cyff, higher thresholds were used in addition to those discussed, in order to account for the higher flows of the channel. Correlations with these higher thresholds however, were poor.

Relationships were also examined for lower thresholds, though no improvement on discharge relationships were made, and thus the 0.3 m^3s^{-1} and 0.5 m^3s^{-1} thresholds were assumed to be critical in entraining and transporting bedload. This evidence is further backed up by the original data, where little or no bedload is moved in periods with extended low flows and few flood peaks (periods *I*, *Ma*, and *S*).

DURATION OF FIELDWORK

Figures 4.11 and 4.12 initially compare the relationship between bedload trap output and total discharge from the Nant Tanllwyth and the Afon Cyff. The most striking feature is to demonstrate the significantly lower yields of bedload in the Afon Cyff, despite much greater discharge. Figure 4.11 demonstrates the stronger relationship in the Nant Tanllwyth with an r^2 of 0.84 from a simple discharge / bedload relationship. It could be assumed therefore, that future-changing trends in the Nant Tanllwyth would be more easily identifiable than in the Afon Cyff, which has an r^2 of 0.59. The full equations are shown in Table 4.7.

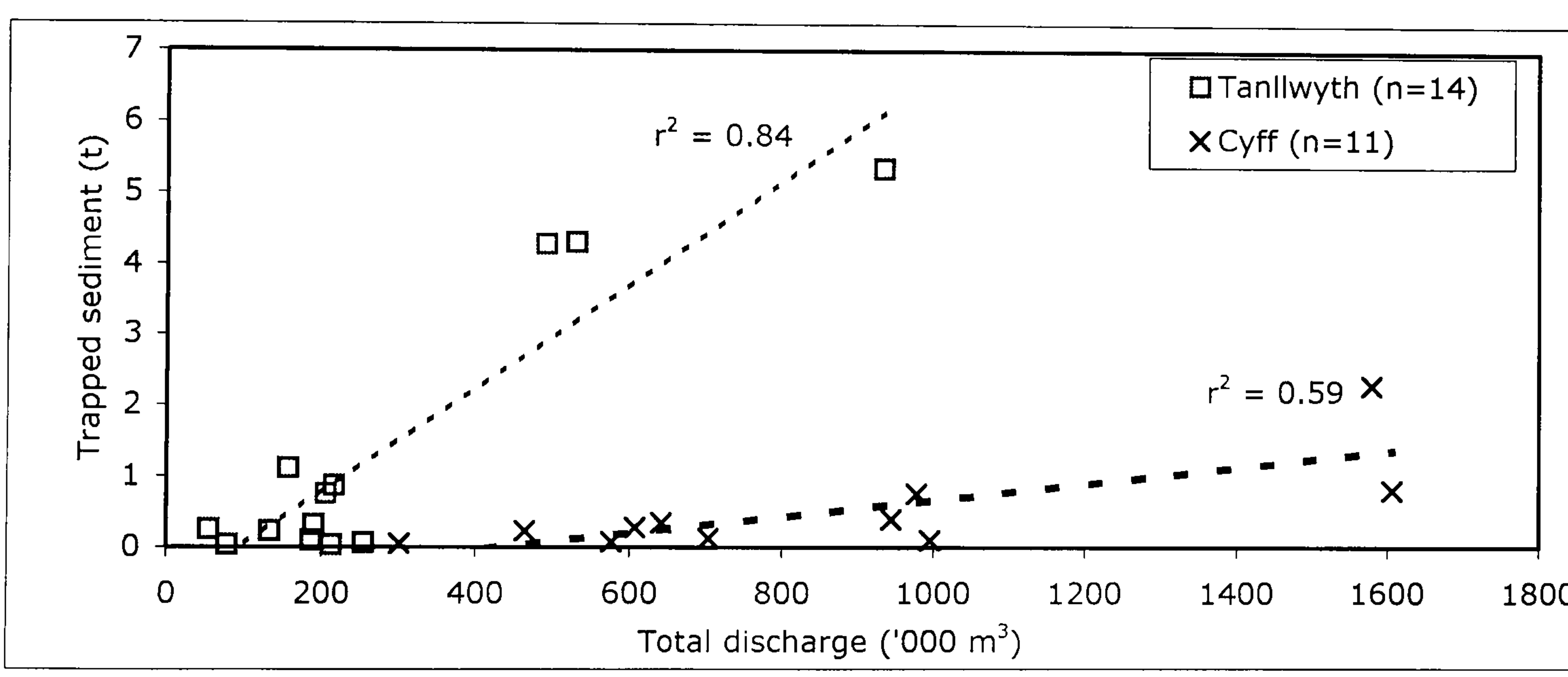


Figure 4.11. Total stream discharge compared to bedload trap outputs in Afon Cyff and Nant Tanllwyth

Figure 4.12 continues to show the differences in magnitude between the Afon Cyff and Nant Tanllwyth, but shows how the relationships are improved using a discharge over threshold (0.3 m^3s^{-1}), indicating that low flows are not related to bedload transport in the channels.

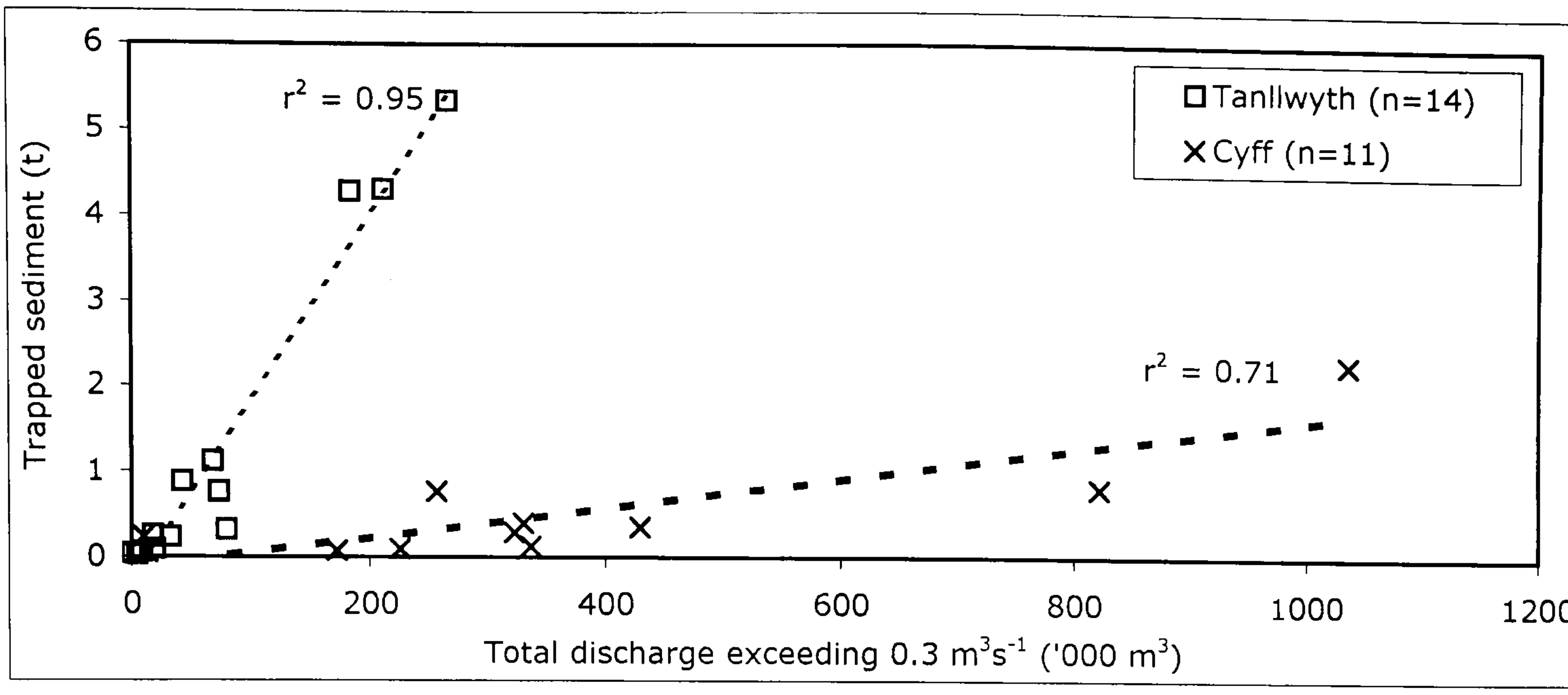


Figure 4.12. Total excess stream discharge above 0.3 m^3s^{-1} threshold with bedload trap outputs in Afon Cyff and Nant Tanllwyth

Table 4.7. Equations showing bedload relationships in Afon Cyff and Nant Tanllwyth

	Nant Tanllwyth	**Afon Cyff**
Initial approximation based on total discharge	Y = 0.0073x - 0.68	y = 0.0012x - 0.50
r^2	0.84	0.59

Further analysis of these data is given in Figures 4.13 to 4.17 (Nant Tanllwyth) and 4.18 to 4.22 (Afon Cyff). The Figures show the relationships between flow threshold parameters and total bedload output, as well relationship with time.

Figures 4.13 to 4.17 show the relationships between total bedload outputs and various controlling parameters in the Nant Tanllwyth.

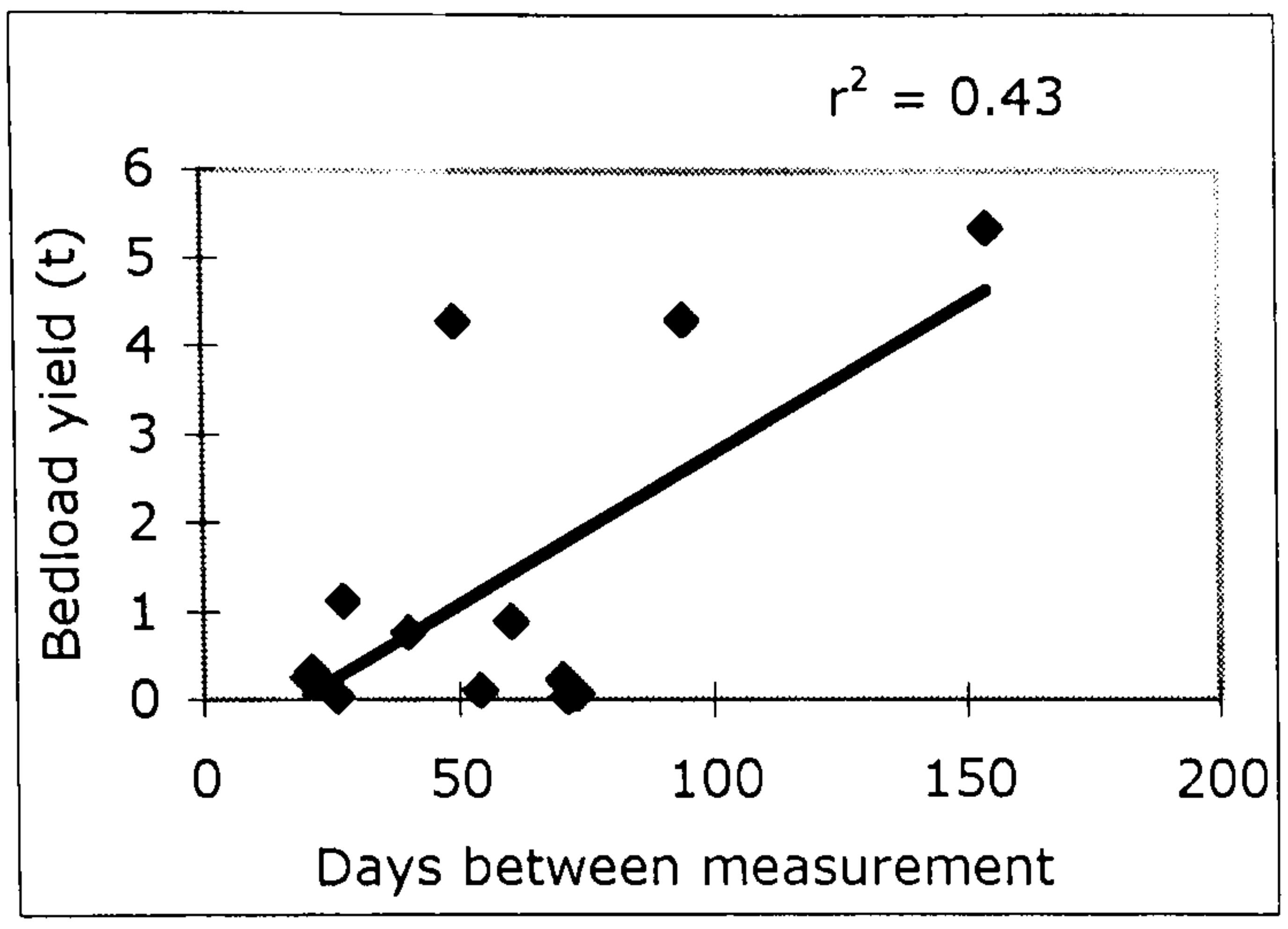


Figure 4.13. Nant Tanllwyth: time and bedload yield per dip

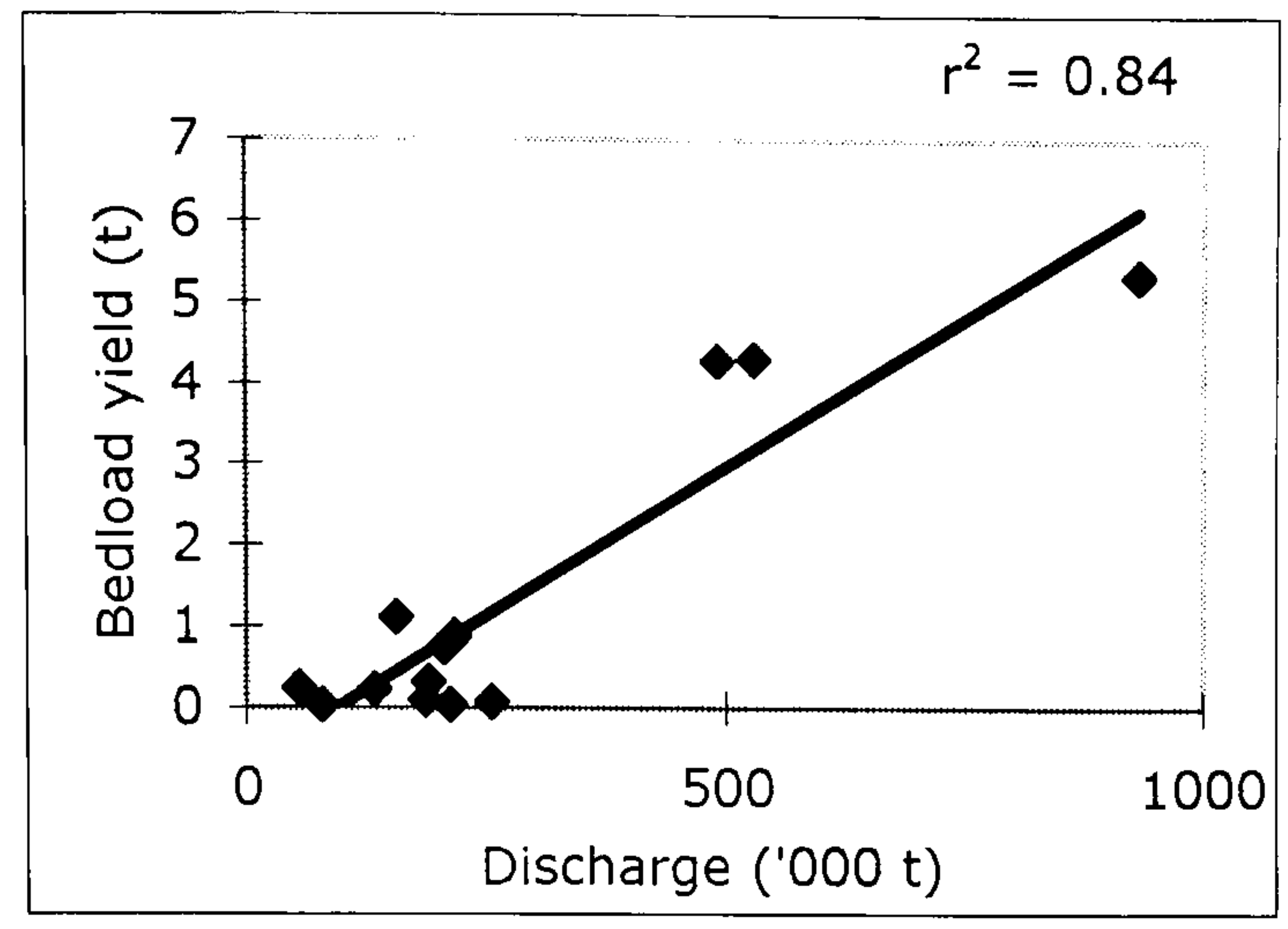


Figure 4.14. Nant Tanllwyth: discharge and bedload yield per dip

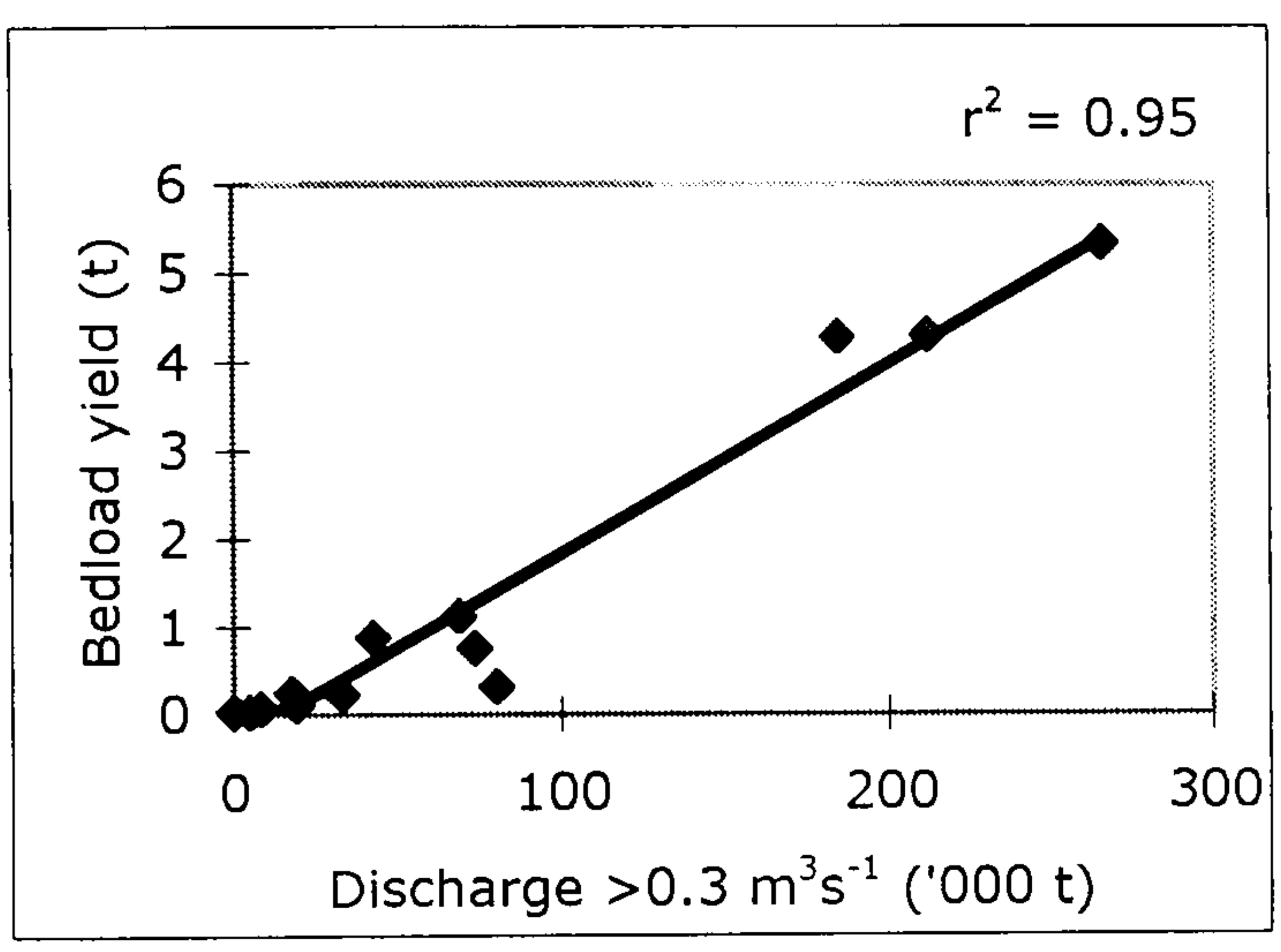


Figure 4.15. Nant Tanllwyth: discharge > 0.3 m^3s^{-1} and bedload yield per dip

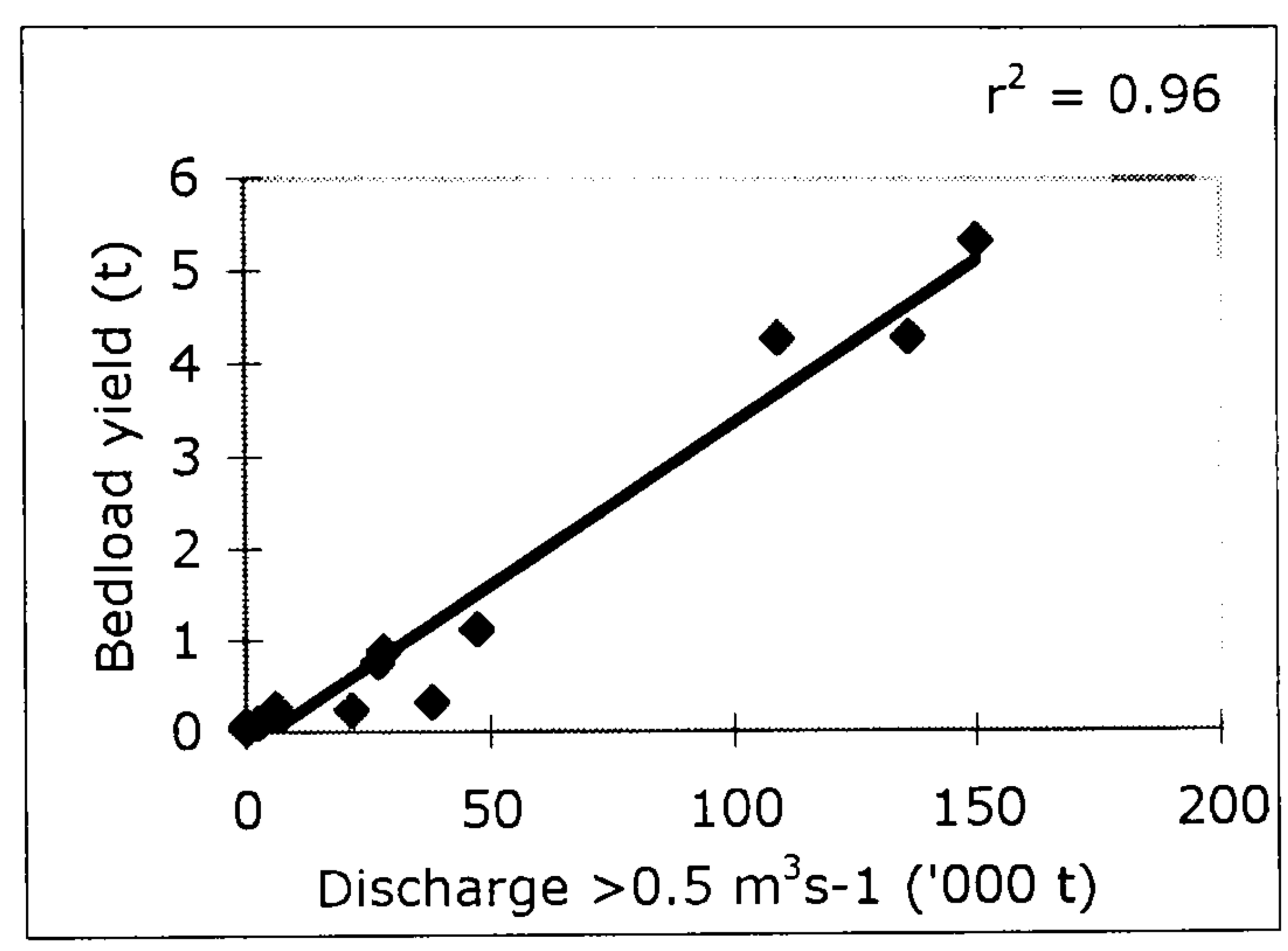


Figure 4.16. Nant Tanllwyth: discharge > 0.5 m^3s^{-1} and bedload yield per dip

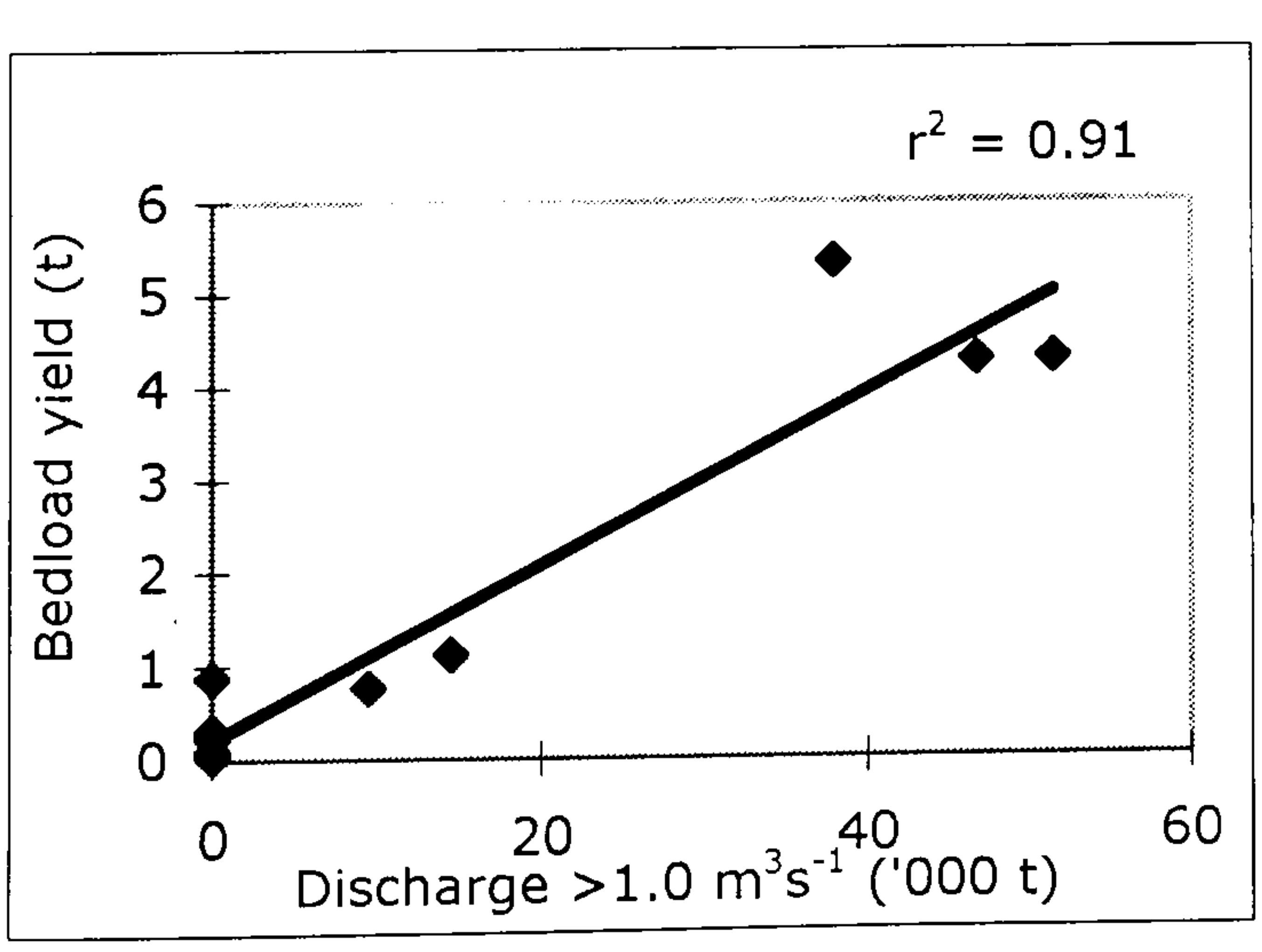


Figure 4.17. Nant Tanllwyth: discharge > 1.0 m^3s^{-1} and bedload yield per dip

Figures 4.18 to 4.22 below show the relationships between total bedload outputs and various controlling parameters in the Afon Cyff.

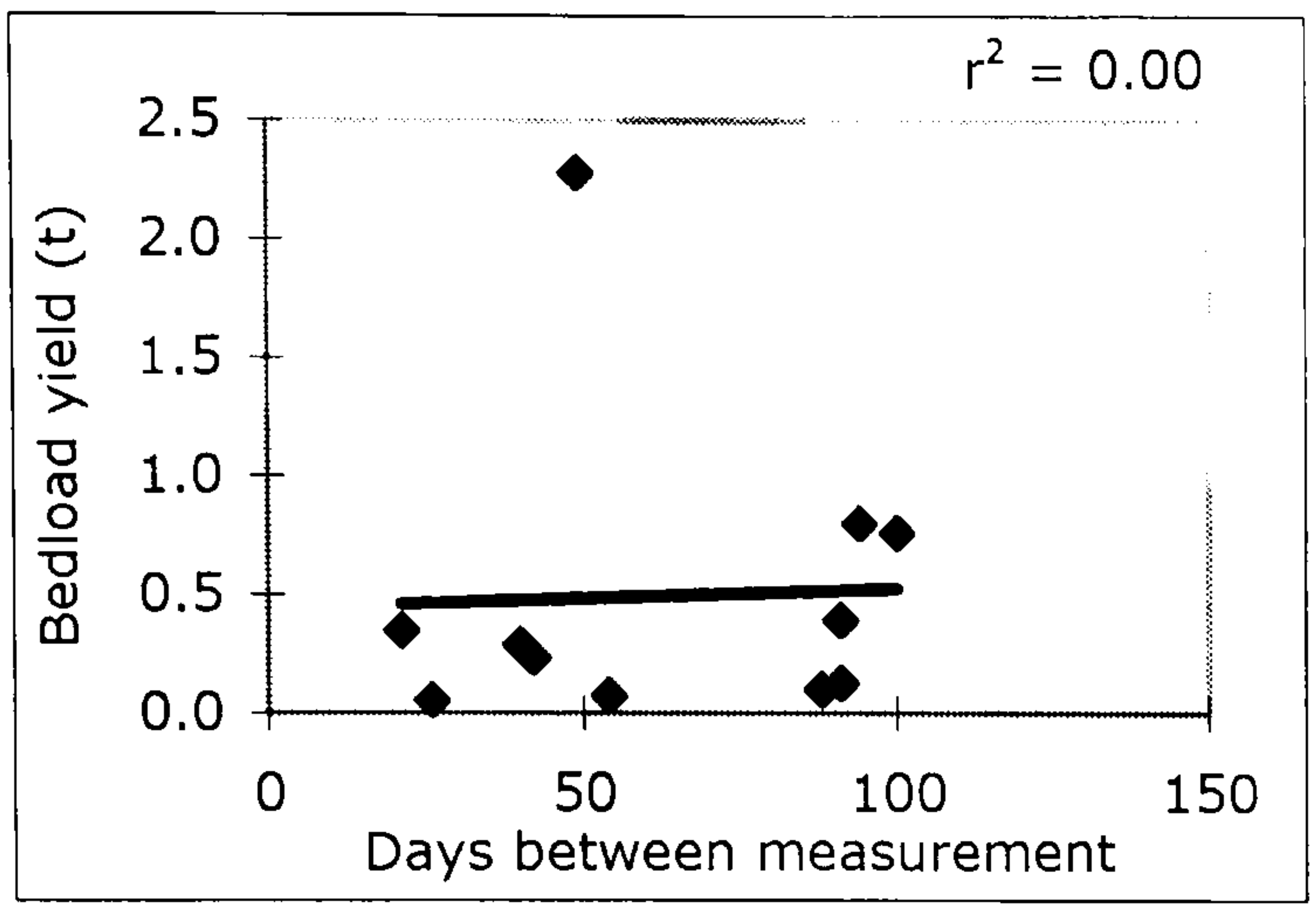


Figure 4.18. Afon Cyff: time and bedload yield per dip

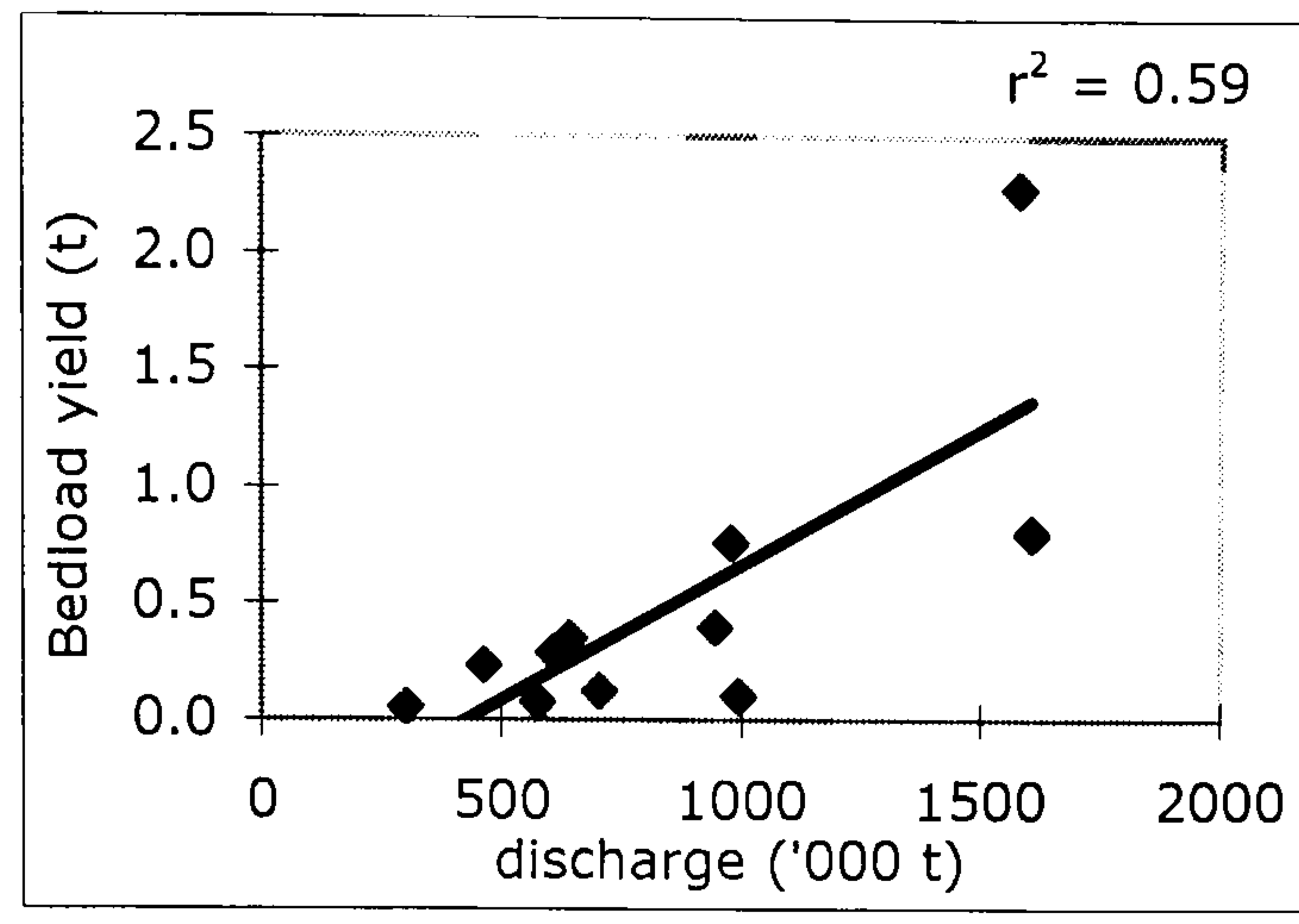


Figure 4.19. Afon Cyff: discharge and bedload yield per dip

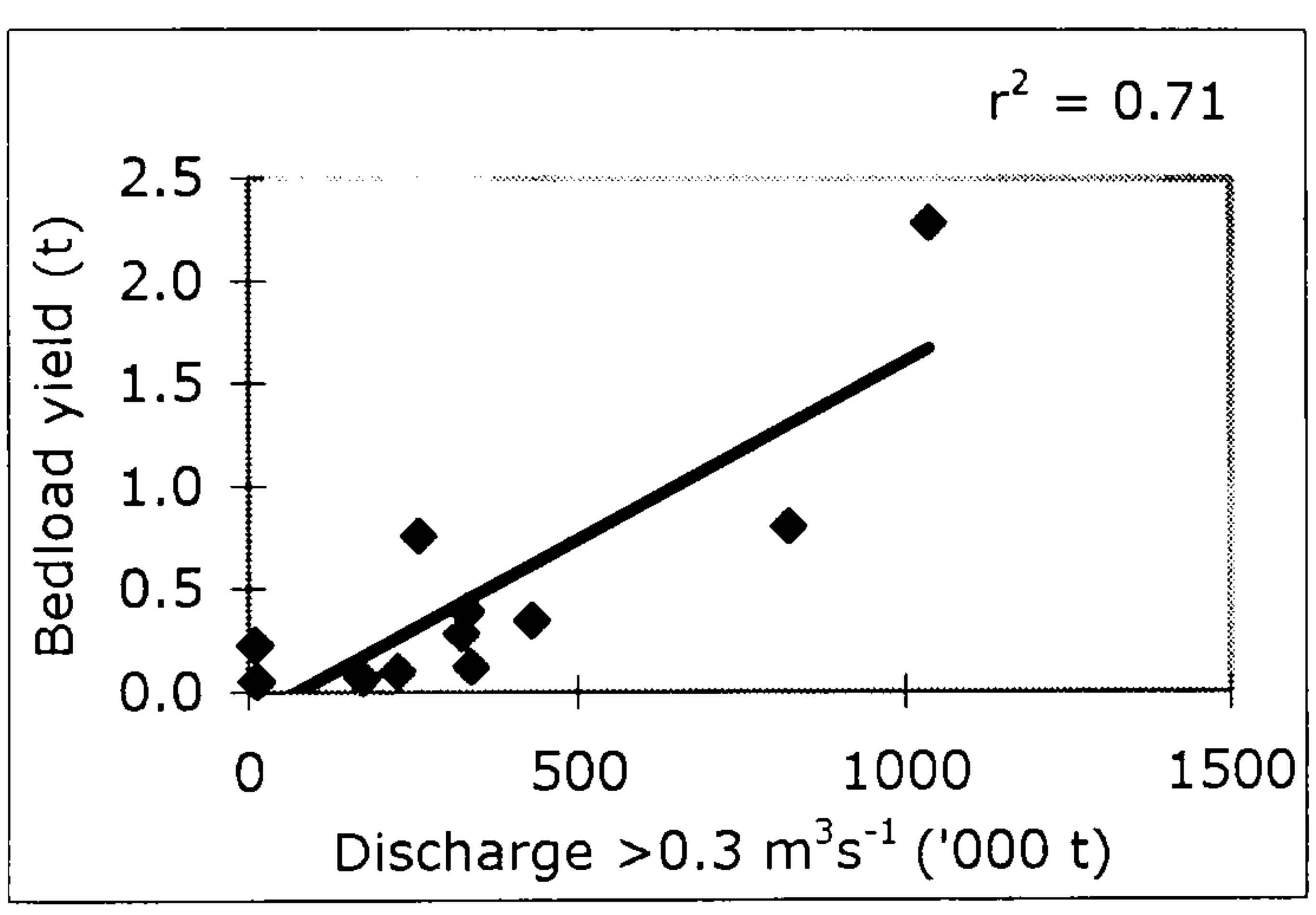


Figure 4.20. Afon Cyff: discharge > 0.3 m^3s^{-1} and bedload yield per dip

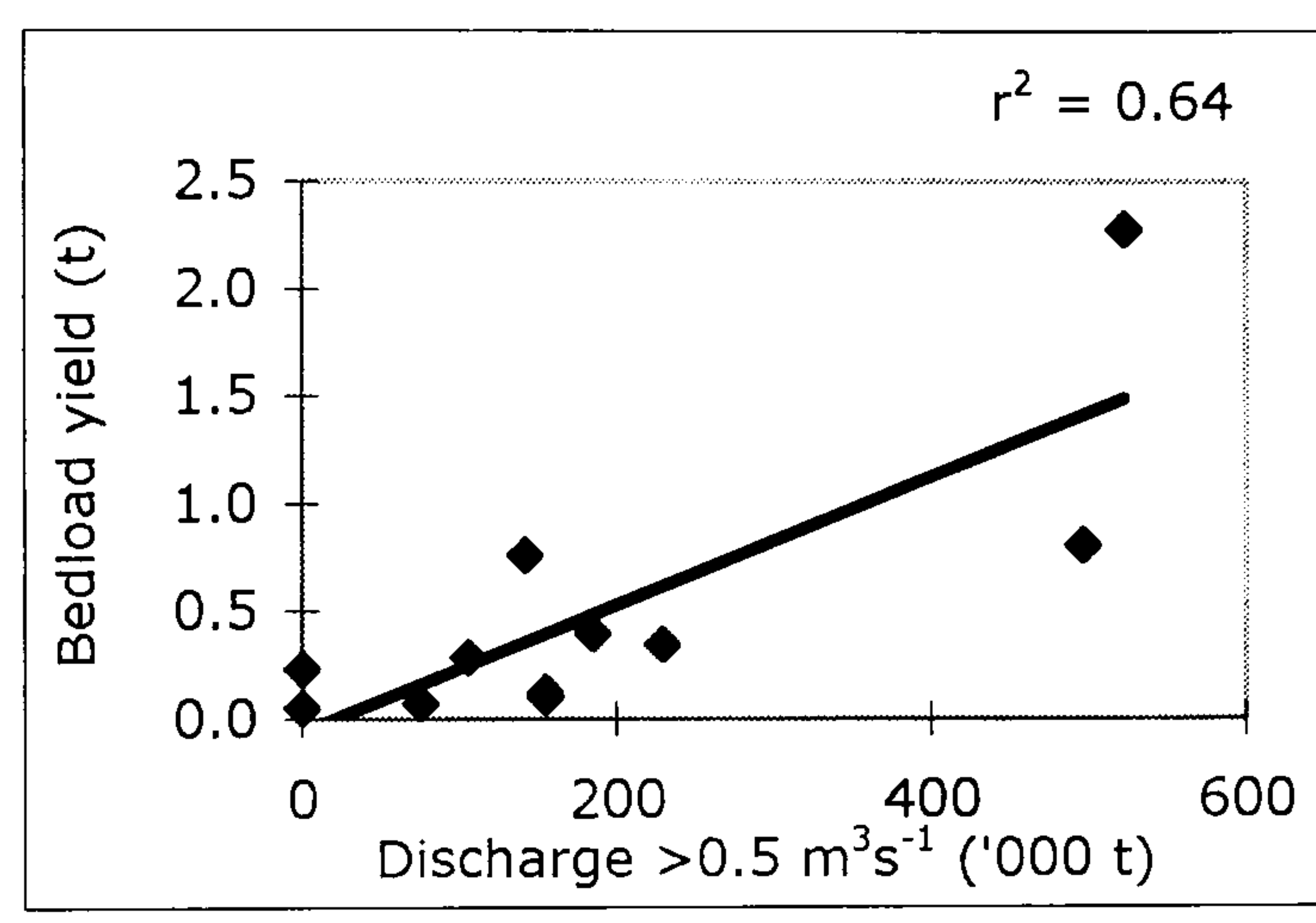


Figure 4.21. Afon Cyff: discharge > 0.5 m^3s^{-1} and bedload yield per dip

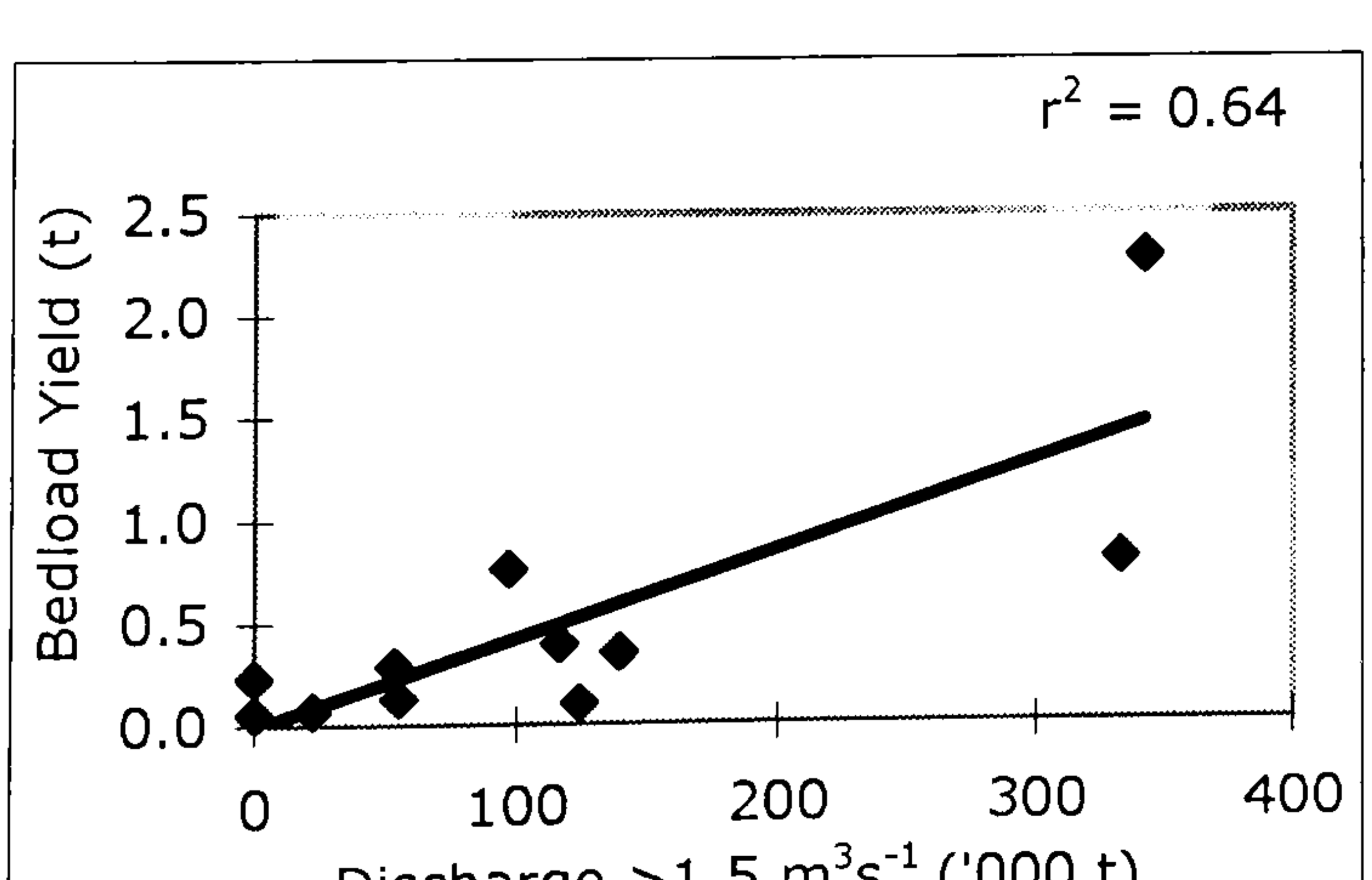


Figure 4.22. Afon Cyff: discharge > 1.0 m^3s^{-1} and bedload yield per dip

In the Nant Tanllwyth, as in all figures, it is illustrated that in the short term, there is a poor relationship between bedload outputs and length of monitoring period (Figure 4.13). Relationships with flow parameters are better: $r^2 = 0.95$ (n=13, p<0.001) for a 0.3 m^3s^{-1} threshold and slightly better r^2 value of 0.96 for a 0.5 m^3s^{-1} threshold, though the value of n is reduced to 11 (p<0.001). The sample decreases with greater magnitude flow events (threshold 1.0 m^3s^{-1}), and furthermore the relationship decreases to $r^2 = 0.91$ (n=8, p<0.001).

These data describe a stream that exhibits flow-limited bedload transport characteristics: where floods capable of entraining bedload arise, the bedload available is transported through the system efficiently.

In the Afon Cyff, however, the relationship is less clear. The best, though far from conclusive r^2 value for total bedload outputs is obtained, as in the Nant Tanllwyth, by correlating a threshold of 0.5 m^3s^{-1}. However the relationship r^2=0.71 is not as strong (n=11, p<0.01). With reduced relationships at higher flows (despite the Afon Cyff experiencing flows of three times the magnitude of the Nant Tanllwyth), it could be concluded that the initial entrainment and transport thresholds of the two channels are similar. The nature of sediment availability has changed with the Afon Cyff exhibiting characteristics of a supply-limited bedload system.

The possible reasons for this, including the availability of bedload, its matrix, composition and bed armouring will be discussed in section 5.

THE HARVESTING OF THE NANT TANLLWYTH

In order to disentangle the effect of harvesting on total bedload outputs, analysis of yield before and after harvesting operations was undertaken. Table 4.8 below shows the total bedload output before and after harvesting as well as the yield per unit flow for the two phases.

Since harvesting took place between dip periods, the figures used begin at the start of the duration of fieldwork and continue up to the 3rd May 1996 for the pre-harvest period for total bedload data. Analysis of the period between the dips however, shows only a very low bedload output during that period and the effects on the results is deemed to be negligible.

Table 4.8. Comparison of pre- and post-harvesting bedload outputs in the Nant Tanllwyth.

	Pre-harvesting	Post-harvesting	Percentage change
Total (tonnes)	7.74	10.35	**38.1%**
Yield per million m^3	4.21	5.12	**21.6%**
Yield per million m^3 over threshold (0.3 m^3s^{-1})	16.75	17.54	**4.7%**
Yield per million m^3 over threshold (0.5 m^3s^{-1})	30.84	31.26	**1.3%**

On initial examination, the data show that total bedload outputs increase significantly after harvesting, a total tonnes increase of 38.1%, compared with the slightly shorter pre-harvesting phase. However, investigation of the data in Table 4.8 shows an interesting trend. Having earlier established the good relationship between bedload output and discharge thresholds in the Nant Tanllwyth, these relationships can be relied upon in an analysis of pre- and post-harvest phases. This analysis, making the data dimensionless using total discharge ('000 m^3) above the thresholds shown in Table 4.8, shows that little difference can be seen between the two phases and this difference is certainly not significant. When the phases are analysed using the 0.5 m^3s^{-1} threshold, there is only a 1.3 % difference in the outputs. Using correlation coefficients for the pre- and post-harvesting periods did not show any difference in the relationships and when plotted, both regression lines were near identical.

A COMPARISON WITH THE AFON CYFF

The availability of a paired catchment allows us to make a two pronged examination on the dynamics of the geomorphological system, by providing a control, and removing many of the variables that cause problems when making comparisons. However, one of the main differences between the Afon Cyff and Nant Tanllwyth is that evidence suggests that the pattern of bedload outputs is different and may be controlled by different mechanisms. The excellent relationship between the 0.3 m^3s^{-1} discharge threshold and bedload output obtained in the Nant Tanllwyth is not mirrored in the Afon Cyff. It would be futile to attempt a duplicate of Table 4.8 for the Afon Cyff and expect the data to be useful, as there is simply no available relationship in the Afon Cyff to allow such a comparison.

SUMMARY

It can be concluded therefore, that the harvesting of the portion of the Nant Tanllwyth catchment has had no discernible effect, within the parameters studied, on the total bedload outputs of the Nant Tanllwyth. This short summary is neither exhaustive, nor representative of the bedload particle dynamics to be discussed in section 4.3.

4.3. Individual particle dynamics

4.3.1. Introduction

Tracer clasts were tracked downstream to provide a detailed picture of sediment flux in both channels and to augment the data available on total bedload outputs (monitored bedload throughputs in the bedload traps in section 4.2). Magnetically-tagged, natural tracer clasts were seeded over a period of 28 months in both experimental sections of the channels described in section 2.5. Tracing methodology and standards are discussed in section 3.5 and a full discussion of resolving missing tracers is given later in this introduction. Data were related to duration of fieldwork, individual monitoring-periods and in the Nant Tanllwyth, to pre-harvest and post-harvest phases. As with the data from the bedload traps, travel distances are also related to discharge thresholds.

The data are presented in order of analysis technique. First results in section 4.32 describe the mean travel distances of clasts based on each trace and relates these step lengths to flood magnitude and flow parameters. Section 4.33 examines the relationship between step length and total travel distance and trace size and section 4.34 examines the effect of tracer shape on step and travel distance. Finally, section 4.35 examines the influence of conditions of entrainment on travel distance.

Monitoring individual clasts also gave the opportunity for an abrasion study utilising natural clasts, and relating abrasion to travel distances and burial. This is discussed separately in section 4.4.

INITIAL DATA PRESENTATION.

Monitoring of individual particle dynamics commenced in the Nant Tanllwyth on 3rd February 1995, with the seeding of 20 tracer clasts with b-axis ranging from 22 - 87 mm.

These tracers were evaluated until 24th May 1995, when their design was found to be acceptable. Seeding of further tracers in the Nant Tanllwyth took place on 15th October 1995 (46 into main channel, 20 in small tributary) and 11th January 1996 (101 in main channel). In the Afon Cyff, 45 tracers were seeded on 24th May 1995, and subsequent seeds were made on 11th August 1995 (51 tracers) and 20th February 1996 (104 tracers).

Total monitoring periods for the Nant Tanllwyth and Afon Cyff were therefore 850 days and 740 days respectively. In the forested Nant Tanllwyth, 10 traces were made, and in the Afon Cyff, 5 full traces were made. Limitations of fieldwork time and access to the Afon Cyff catchment account for the discrepancy in monitoring intensity. In addition to the tracers in the main channel in the Nant Tanllwyth, 20 tracers were entered into a small tributary of the upper Nant Tanllwyth at the top of the study reach. These tracers were seeded at four points spaced at 20 m, 40 m, 60 m and 80 m from the confluence with the Nant Tanllwyth. During the fieldwork none of these tracers were transported into the main channel.

Tracing activity through the two channels is summarised in Table 4.9, which includes the initial recovery rates for each search. It is often difficult in the literature to ascertain by which exact method recovery rates are determined. A full discussion of this is given later in this section. The recovery rates below show the percentage of tracers that are recovered, identified and recorded from the total population of tracers seeded in the channel.

Table 4.9. Summary of work: monitoring of individual tracer step lengths throughout field study period

Date	Nant Tanllwyth.			Afon Cyff.		
	Work	**Total seeded**	**Recovery rate**	**Work**	**Total seeded**	**Recovery rate**
3rd Feb 95	Seed	20				
15th Mar 95	Trace 1	20	100 %			
24th May 95	Trace 2	20	100 %	Seed	45	
27th Jul 95				Trace 1	45	98 %
11th Aug 95	Trace 3	20	100 %	Seed	92	
15th Oct 95	Seed	66				
11th Jan 96	Seed (101) Trace (66) 4	167	83 %			
18th Jan 96				Trace 2	92	60 %
20 Feb 96				Seed	196	
26th Mar 96	Trace 5	167	82 %			
2nd Apr 96				Trace 3	196	89 %
2nd Jul 96	Trace 6	167 (7)[1]	87 %			
1st Oct 96	Trace 7	167 (24)[1]	84 %			
10th Dec 96	Trace 8	167 (30)[1]	72 %			
9th Apr 97	Trace 9	167 (30)[1]	N/A	Trace 4	196	55 %
2nd Jun 97	Removal 10	167 (37)[1]	71 %	Removal 5	196	47 %

[1]***Figures in brackets shows number of tracers' known to have been removed.***

RECOVERY RATES AND TRAVEL DISTANCES

The issue of recovery rates is addressed in this section [rather than methods] as it is a direct consequence of fieldwork measurement that the issues arose. Prior to the full experiment, it was not possible to determine the statistical distribution of how pebbles would be lost, therefore the issue is explained in this section.

The analysis of clast travel distances is hampered by the problems of missing values. During the 28-month period of fieldwork only 49 tracers from the Nant Tanllwyth and 56 from the Afon Cyff were found on every search occasion. These tracers are termed the "subset$_{50}$". This results in a large volume of missing data. Although there are several physical ways in which a tracer is lost (magnet failure, transport through the reach into the bedload trap, deep burial, or even theft by walkers!) the losses can be treated in two just two ways: -

1 A tracer is lost, and is not subsequently recovered through the study, and
2 a tracer is lost, but is subsequently recovered in a future trace.

The two scenarios affect consideration and calculation of the following:

1 How to present meaningful recovery rates, and thus estimate overall travel distances?
2 How to assign travel distances to clasts during a trace (where ignoring the value, would incorrectly assign a no travel distance to a reading)?

Presenting recovery rates

The recovery of tracers is based firstly upon the ability of the instrument and fieldworker to establish the magnetic field of the tracer whilst on the bed and secondly, on being able to locate the exact tracer and recover it. Only very rarely was a tracer located by sight alone during a search.

Experience throughout the study showed recovery was difficult in the following situations;

1 When tracers were buried deeply in the bed;
2 in areas where foreign material (e.g. nails, wire and fence material were common, particularly in the Nant Tanllwyth) was present, and
3 in tracers belonging to the smallest size classes.

The percentage of tracers recovered and the distribution of class sizes to which missing tracers belong, is crucial in estimating the overall travel distances of each class size that exist on the bed.

Little emphasis seems to have been placed on this issue in previous literature and in many studies appears to be completely ignored. Tracer recovery rates were analysed in the Nant Tanllwyth and Afon Cyff to examine if a pattern of missing tracers existed and if tracer parameters affected probability of loss. By examining the size distribution of tracers found every time (the $subset_{50}$) and comparing these to the total tracer population, it was shown that tracers from the coarser size ranges were more likely to be recovered than finer clasts. This is shown in Figures 4.23 and 4.24. This selectivity can be explained in two ways:

1 **Tracer characteristics**, magnets used in smaller clasts gave out a smaller magnetic field, or some types, sizes and geologies of tracer may be susceptible to breakage, and

2 **geomorphological reasons**, tracers themselves were more difficult to locate, either due to deeper burial, or due to transport though the experimental reach.

Figure 4.23 shows that in fine class sizes where a significant number of tracers were present, recovery rates were much lower than in the coarse size ranges. This again highlights the deficiency in using tracer distributions to match bed distribution. More appropriate would be to use equal numbers in each class

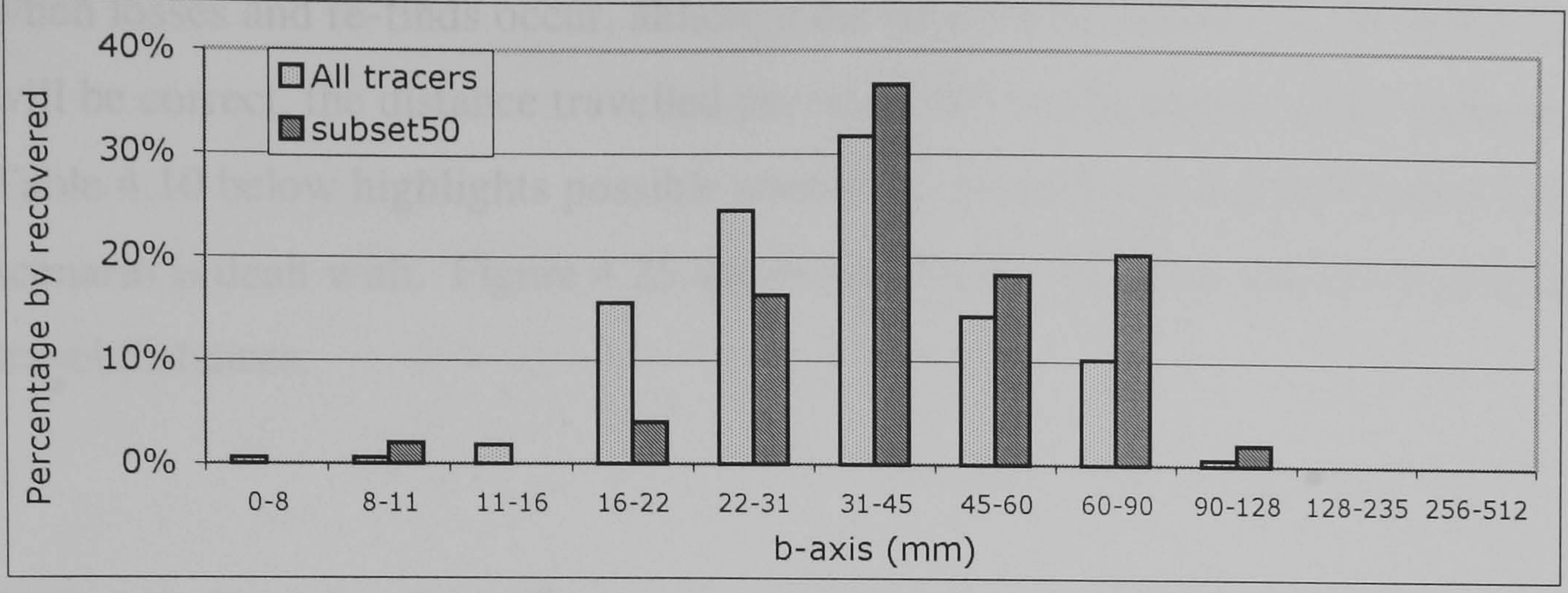


Figure 4.23. Chart comparing the recovery rate of the subset$_{50}$, with total tracer population in the Nant Tanllwyth

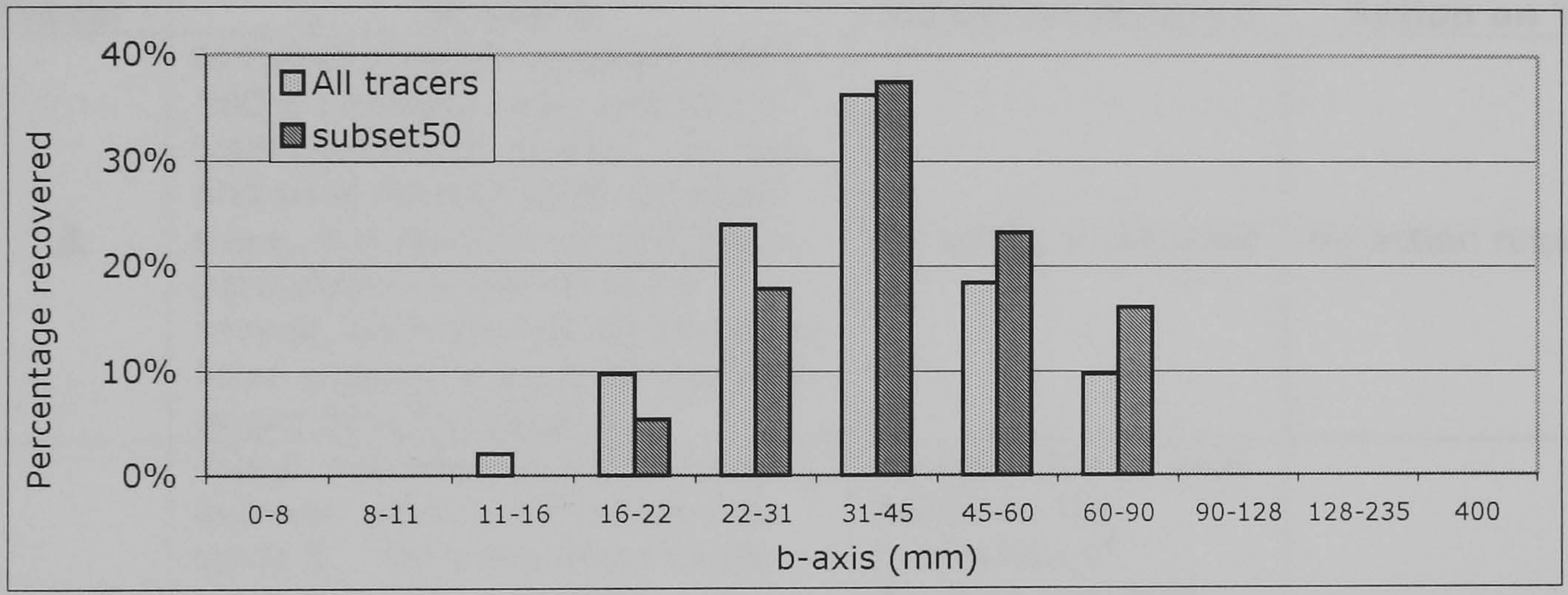


Figure 4.24. Chart comparing the recovery rate of the subset$_{50}$, with total tracer population in the Afon Cyff

On occasion, tracers may have been found but deliberately removed due to construction failure, or impossible identification. This leads to a reduction in total population, but not necessarily a reduction in the recovery rate of subsequent traces.

Assigning travel distances

Travel distances from one trace to the next were calculated from knowing the location of the tracer pebble at both traces. This presents no problem in the case of the subset$_{50}$ as tracers can be assigned travel distances for each trace, and the total travel distance can be attained by summing the calculated travel distances for each trace. However, when losses and re-finds occur, although the total travel distance at the end of the study will be correct, the distance travelled per trace will not be known. The upper part of Table 4.10 below highlights possible scenarios, whilst the lower half shows how each scenario is dealt with. Figure 4.25 shows the routine by which tracers are ascribed travel distances.

Table 4.10. Examples of possible scenarios when tracers are not found

Tracer		Trace ①	Trace ②	Trace ③	Trace ④	Total
A	SEED	10	10	10	10	40
B	SEED	10	-	20	10	40
C		SEED	-	-	40	40
D	SEED	10	10	10	-	30

Tracer	Scenario	Action on distance	Action on Time
A	Is found on each occasion, has a 100% recovery rate, and has a total movement of 40m. As flow and time records exist for each trace, it is easy to ascribe these parameters to the distance moved, each period can therefore have a mean movement per day or per flow threshold.	No action is required	No action required
B	Tracer not been found on trace 2, but was subsequently found on trace 3. The trace distance for trace 3 is 20m, but it is impossible to tell the period in which movement occurred (i.e. between the first and second trace, or the second and third).	Assign trace 2 value based on the proportion of flooding that took place over the period of trace 2, out of T2 and T3. Total of trace 2 and three will be 20m.	No action required
C	Tracer is found only on the last search. Although we do not know when the travel took place, we do know its total travel distance (40m).	Assign all missing cells values based on flood index.	As seed-time is later, total time and flood totals reduced due to reduced monitoring period.
D	Tracer is not found on the last trace. We know its total travel distance at the end of trace 3, but cannot relate that number to any time or flow thresholds after trace 4.	Values normal for traces 1-3, with NO value assigned for trace 4	Total time and flood totals reduced due to reduced monitoring period.

These considerations are summarised in the flow diagram Figure 4.25 below.

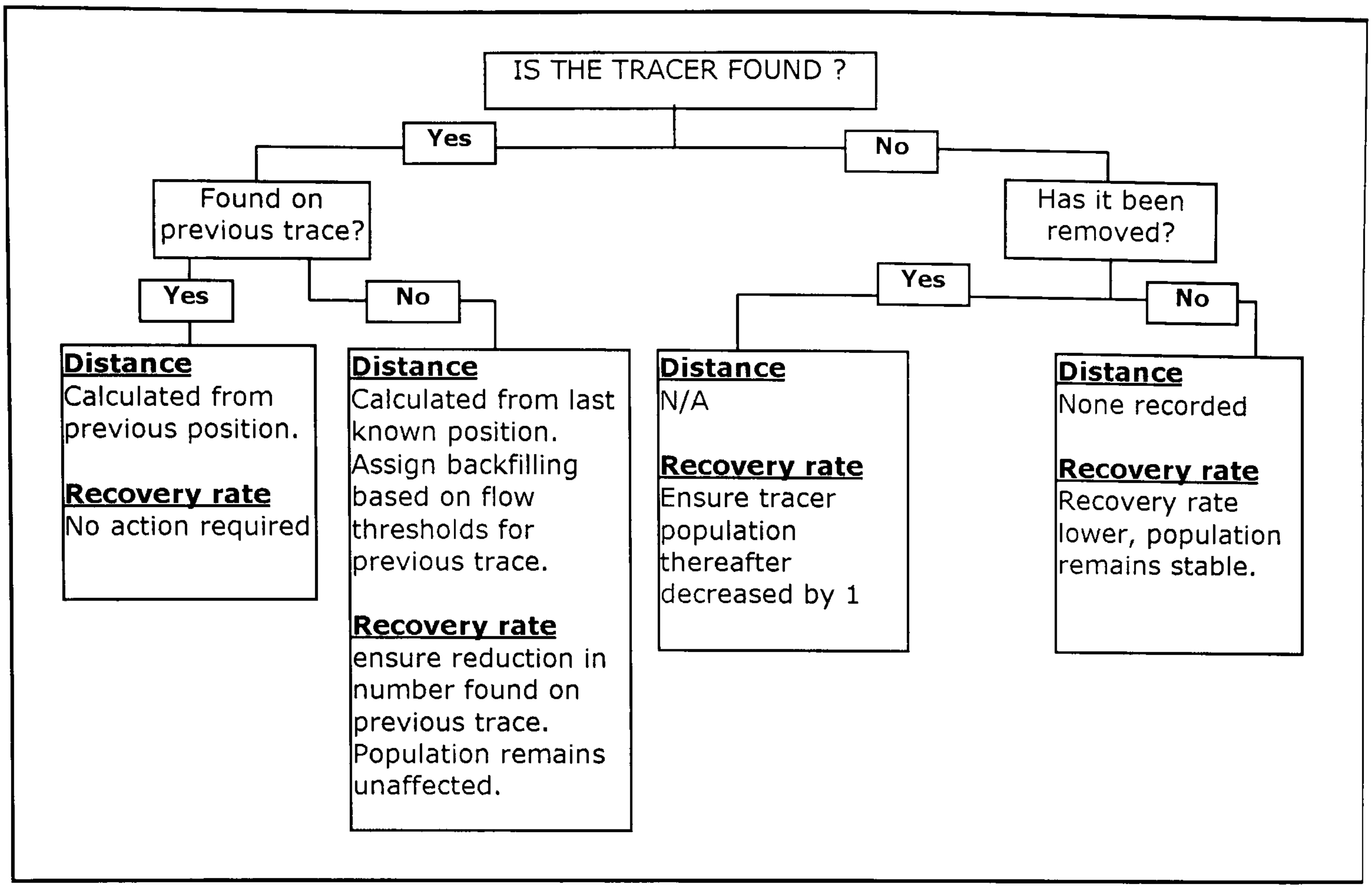


Figure 4.25. Flow diagram showing how a missing tracer is ascribed a value.

Backfilling the dataset

The large number of gaps in the location data caused by lost, or temporarily lost tracers, causes a disproportionately large amount of travel distance data to be rejected. If the only accepted data was that derived from two consecutive traces, 46% of results are removed from the data set. It is desirable to avoid abandoning such useful data whilst at the same time, maintaining the integrity of the data set.

Examining the $subset_{50}$, the mean travel distances for each trace (section 4.32) are almost identical to the remaining (excluding the $subset_{50}$) dataset where only consecutive successful traces are considered. We can therefore deduce that individual tracers that have missing trace values can be *backfilled*. It is known from bedload trap data (section 3.2) and mean individual tracer movements (see Figure 4.26) that a good relationship with the 0.3 m^3s^{-1} threshold is attained ($r^2 = 0.95$, $n=13$, $p<0.001$). Backfilling is undertaken on all missing values using the ratio of flow over the 0.3 m^3s^{-1} threshold in each period of tracing.

This process can be illustrated by examining the fictitious tracer B in Table 4.10. Trace 3 has a travel distance of 20m, whilst no value exists for trace 2. For example, a scenario exists where the flow in period 3 was 25 '000 t and the flow in period 2 was 75 '000 t. The value of period 3 would be 25% of the total travel distance (5 m) and for period 2 75% of the travel distance (15 m). This avoids the incorrect assertion that in period 3, the travel distance was 20 m, and in period 2, zero m. If no backfilling was undertaken, data from both trace 3 and trace 2 would have to be removed.

What backfilling does not do is interpret forward any data, for example, it makes no attempt at predicting movement (in the fictional example) of tracer D in the 4^{th} trace.

The advantages to this backfilling method are as follows:

1 More values are present within the data set, and quality data is not rejected,
2 significantly better coverage at the distribution tails is attained, and
3 traces with poor recovery rates are not misrepresented. This is particularly applicable to trace 9 in the Nant Tanllwyth.

In all tracer results that follow, calculations of travel distances, time and flow units are derived from the length of time the tracer was known to have been in the channel.

4.3.2. Mean travel distances for each trace

INITIAL RESULTS

Table 4.11 shows trace dates and mean step lengths of the total tracer population in the Afon Cyff and Nant Tanllwyth. The figures are derived using all tracers and using the back filling technique for unfound tracers. The table does not account for variations in time and flow conditions for each individual period.

Table 4.11. Trace dates and mean travel distances (m) in the Nant Tanllwyth and Afon Cyff

Date	Nant Tanllwyth.		Afon Cyff	
	Travel distance (m)		Travel distance (m)	
3-Feb-95	**SEED**			
15-Mar-95	**TRACE 1**	7.62		
24-May-95	**TRACE 2**	2.87	**SEED**	
27-Jul-95			**TRACE 1**	0.63
11-Aug-95	**TRACE 3**	1.91		
11-Jan-96	**TRACE 4**	8.60		
18-Jan-96			**TRACE 2**	5.74
26-Mar-96	**TRACE 5**	8.89		
2-Apr-96			**TRACE 3**	1.64
2-Jul-96	**TRACE 6**	5.59		
1-Oct-96	**TRACE 7**	3.35		
10-Dec-96	**TRACE 8**	29.67		
9-Apr-97	**TRACE 9**	20.04	**TRACE 4**	41.88
2-Jun-97	**TRACE 10 and REMOVAL**	2.52	**TRACE 5 and REMOVAL**	5.36
Sum of all traces		91.06		55.26

The data in Table 4.11 show the variation in travel distances for individual clasts. Mean distances for each trace vary from 1.91 m to 29.67 m in the Nant Tanllwyth and from 0.63 m to 41.88 m in the Afon Cyff. The greatest mean travel distances in the Nant Tanllwyth took place in the post-felling period, during the winter of 1996-97. Maximum travel distances in the Afon Cyff took place during the final trace between

April and June 1997. The mean travel distance for all tracers over all traces in the Nant Tanllwyth is nearly double that for the Afon Cyff, 91.06 m and 55.26 m respectively.

ANALYSIS BY TIME AND FLOW THRESHOLDS

Table 4.12 below standardises the data described in Table 4.11, by relating travel distances to time and flow over the 0.3 m^3s^{-1} threshold. Section 4.2 has established the link between bedload trap data and the 0.3 m^3s^{-1} threshold and again, although other thresholds were tested on the tracer data, the 0.3 m^3s^{-1} proved to be the most successful.

Table 4.12. Mean travel distances for each trace, related to time and flow thresholds

Date	Nant Tanllwyth.		Afon Cyff	
	m day^{-1}	m '000 t^{-1}	m day^{-1}	m '000 t^{-1}
3-Feb-95				
15-Mar-95	0.19	0.06		
24-May-95	0.04	0.51		
27-Jul-95			0.01	0.007
11-Aug-95	0.02	0.11		
11-Jan-96	0.06	0.08		
18-Jan-96			0.03	0.008
26-Mar-96	0.12	0.12		
2-Apr-96			0.02	0.004
2-Jul-96	0.06	0.11		
1-Oct-96	0.04	0.08		
10-Dec-96	0.42	0.11		
9-Apr-97	0.17	0.09	0.11	0.011
2-Jun-97	0.05	0.13	0.10	0.021
Mean	0.12	0.09	0.08	0.01

Table 4.12 continues to show variation in transport rates on a by trace basis, particularly in terms of time. In the Nant Tanllwyth, these rates range from 0.02 m day^{-1} to 0.42 m day^{-1} (a variation by a factor of 20). The Afon Cyff also shares a wide variation, but daily rates show a lower range from 0.01 m day^{-1} to 0.1 m day^{-1} (a variation factor of 10). Again, the mean travel distance computed for all tracers over all traces in the Tanllwyth is 1.5 times greater than for the Cyff, 0.12 m day^{-1} compared with 0.08 m day^{-1} respectively. However, the travel distances which take account of flow show

much greater contrasts between the two channels, with the Tanllwyth mean being 9 times greater, 0.09 m '000 t^{-1} as compared with the Cyff at 0.01 m '000 t^{-1}.

Tracers in the Nant Tanllwyth travel on average 50 % further than their counterparts in the Afon Cyff shown by analysing tracer movements on a time (m day^{-1}) only basis. These data are derived using the total distance moved by all individual tracers and the total time for which all tracers were monitored (accounting for tracers seeded or lost partway through the experiment). Tracers in the Nant Tanllwyth travel on average of 0.12 m day^{-1} whereas tracers in the Afon Cyff travel 0.08 m day^{-1}.

To place these results in context, it is useful to review from section 1 the differing channel characteristics of the two channels. The Afon Cyff has a significantly greater discharge than the Nant Tanllwyth and achieves flood peaks, some three times higher. The thalweg depth of the Afon Cyff is deeper, whilst channel slope is greater in the Nant Tanllwyth. Billi (1986) highlights the step-pool nature of both channels and shows greater riffle numbers within the Afon Cyff, along with greater pebble clustering.

As with the total bedload flux examined in the bedload traps, the relationship with flow thresholds is a more useful and geomorphologically robust measure. Although variation between the channels still exists by comparison with the 0.3 m^3s^{-1} threshold, variation becomes consistently lower. Values range from 0.06 m '000 t^{-1} and 0.51 m '000 t^{-1} (factor of 8) in the Nant Tanllwyth, and between 0.004 m '000 $t^{-1}$and 0.021 m '000 t^{-1} (factor of 5) in the Afon Cyff. The high value in the Nant Tanllwyth (a search of only 20 tracers on 24th May 1995) is not caused solely by large mean travel distance. It is the combination of a small flood index and unusually large travel distance during the period.

The relationship between the 0.3 m^3s^{-1} threshold and tracer travel distance is therefore examined further. Travel distances in the Nant Tanllwyth are shown in Figure 4.26, where the x-axes shows flood index above 0.3 m^3s^{-1} and y-axes show the mean travel distance for all tracers.

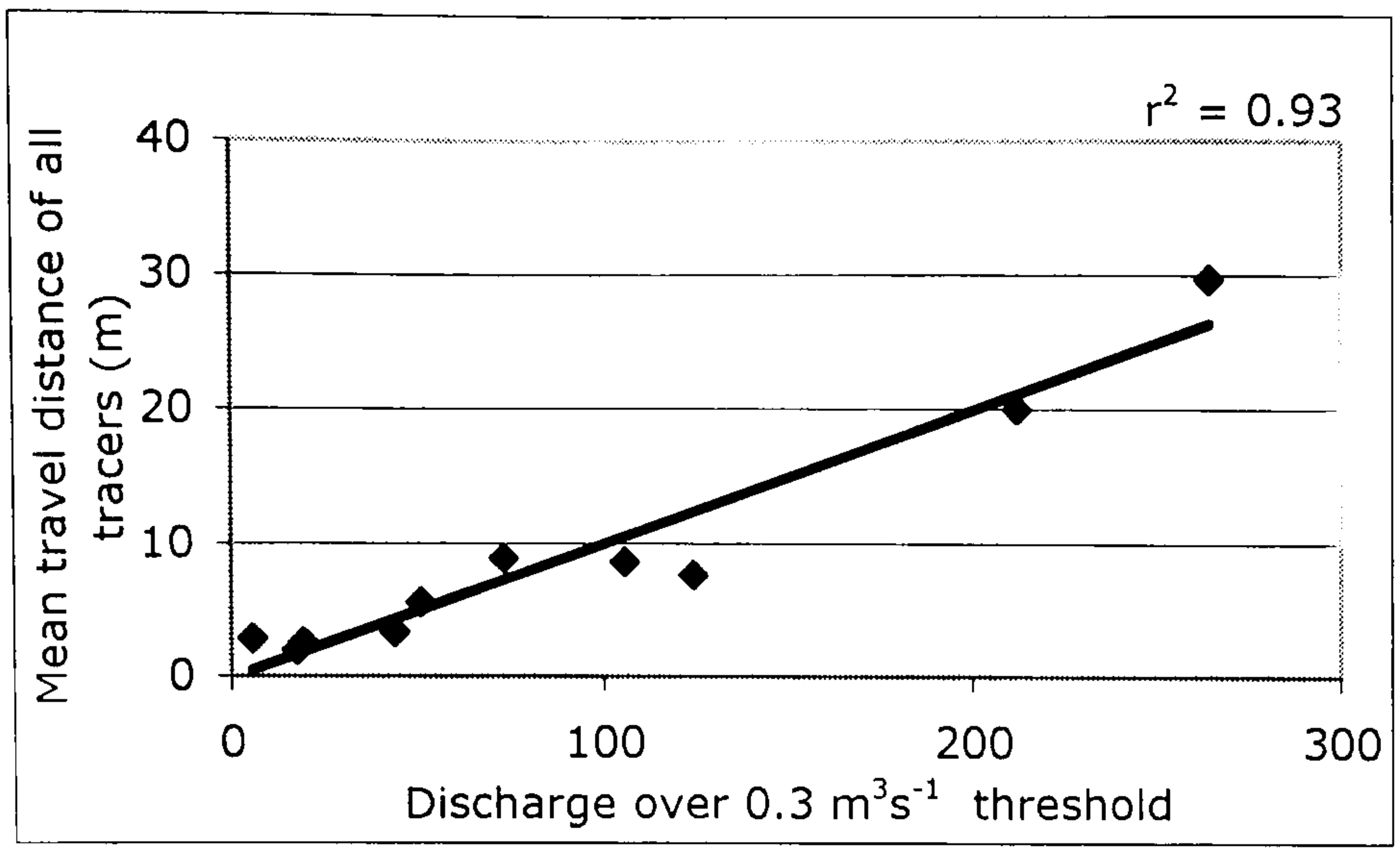


Figure 4.26. Nant Tanllwyth: relationship between the 0.3 m^3s^{-1} flow threshold and mean travel distance of all tracers for each trace

When examined on a trace by trace basis, both rivers show travel distance is dependent on the flow over 0.3 m^3s^{-1} threshold, though the number of traces in the Afon Cyff makes analysis inconclusive. The strong relationship in the Afon Cyff however, is due to the outlying point (trace 4) and cannot be relied upon for statistical significance. Without the outlying point, the plot has an r^2 of only 0.35 (n=4).

FELLING IN THE NANT TANLLWYTH CATCHMENT

The date for felling in the Nant Tanllwyth has been defined as 2nd April 1996. With a trace occurring in the Nant Tanllwyth on 26th March 1996, the pre- and post-harvest phases are easily delimited for tracer data.

A comparison of lumped data before and after harvest, shows that during the pre-harvest phase mean annual travel distance of all size classes was 31.75 m, whereas during the post-harvesting phase, mean annual travel distances increased to 47.77 m. These figures do not account for flood intensity over the period (data available in section 4.1.)

More usefully, based on the proven relationship with the flood intensity 0.3 m^3s^{-1} threshold, the data can be shown as travel distance per unit flow above the threshold. These data are compared using a *t*-test in Table 4.13 below. Mean travel distance of clasts increases after felling, when the data has been made dimensionless using the 0.3 m^3s^{-1} threshold, and is statistically significant at the $p<0.001$ level.

Table 4.13. *t*-test comparing total pre-harvest and post-harvest tracer movements based on 0.3 m^3s^{-1} flood index in the Nant Tanllwyth

	Pre-felling	Post-felling
Mean	0.07	0.11
Variance	0.005	0.01
Observations	164	153
P (t<=t) two-tail	0.001	

Data for this test are derived from all tracers, monitored before and after felling operations, and based on the distance moved of each tracer before and after the felling period.

mean tracer travel distances increased significantly in the post-harvesting phase. To ensure outlying values were not controlling the outcome of the *t*-test, further tests were made removing the ends of the distribution and no changes in the value of *t* were found. We can be confident that the felling period has had an effect in increasing the transport of *in situ bed* sediment in the Nant Tanllwyth.

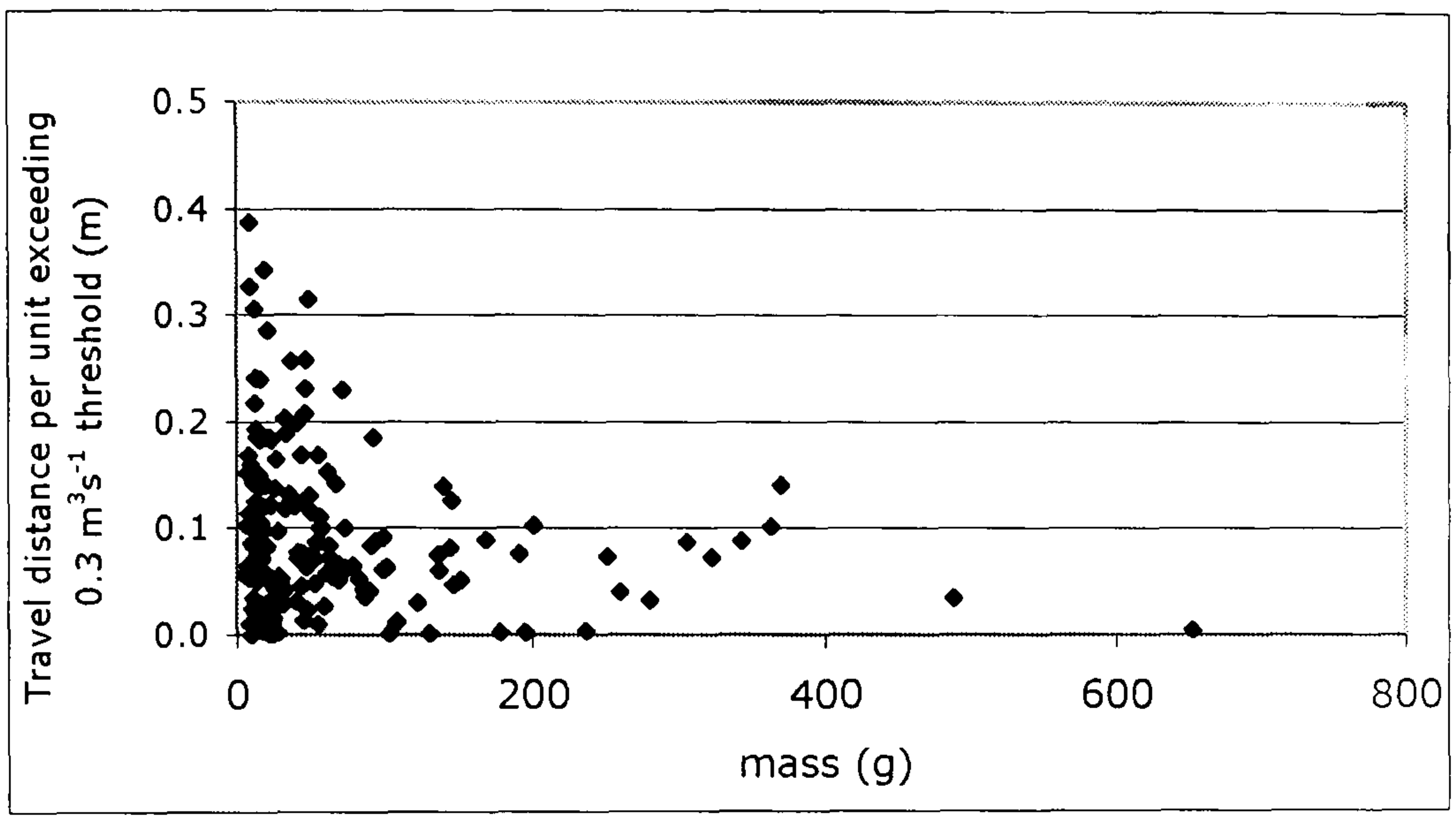
4.3.3. Analysis of flux by particle size

INTRODUCTION

Previous literature on the effects of particle size on sediment flux is discussed in section 2.1.2. In this section, it is intended to examine the controlling parameters of both b-axis and mass on the flux of sediment downstream. Research in the Balquhidder catchments showed forest operations to change the size distribution of sediment inputs (Stott 1996, 1997b). Tracers larger than the median size of the bed were found to have a steep decline in mobility as discussed by Church and Hassan (1992) in a review from several papers.

ANALYSIS BY B-AXIS AND MASS

Figures 4.27 and 4.28 show the total travel distance of each tracer compared to mass of each tracer in the Nant Tanllwyth and Afon Cyff respectively. Figures 4.29 and 4.30 show the equivalent relationships the using the b-axis. Travel distance is equalised using the 0.3 m^3s^{-1} threshold and without this, the variation in the time tracers spent in the channel would control the results.



Points are derived from each individual tracer's total distance divided by flow over 0.3 m^3s^{-1}.

Figure 4.27. Total travel distance of individual clasts compared to mass in Nant Tanllwyth

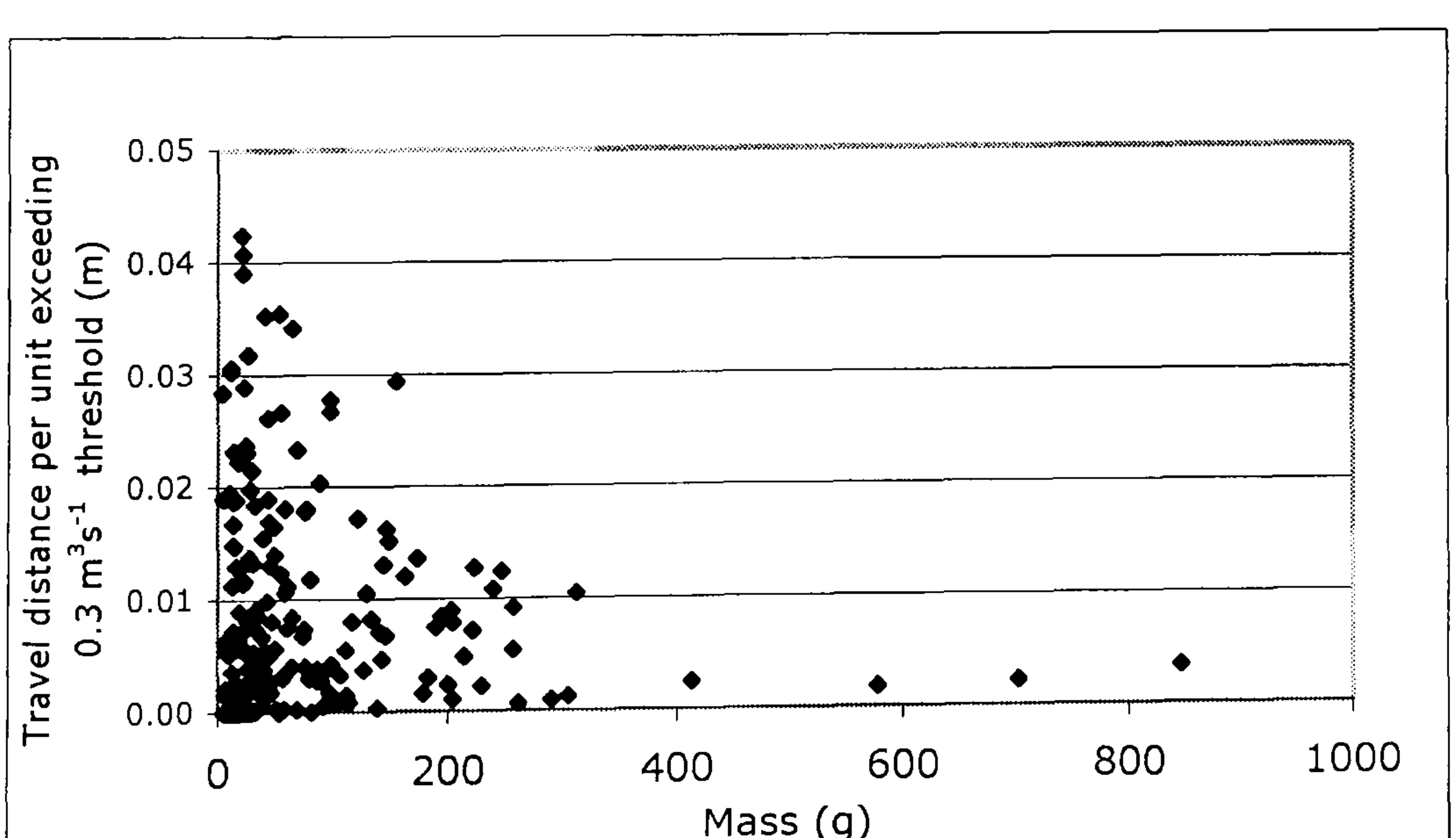


Figure 4.28. Total travel distance of individual clasts compared to mass in Afon Cyff

Within both channels, the relationship between travel distance and mass is enveloped into a range that appears to limit the distance that heavier clasts can travel. Within each particle size range however, a large variation in travel distance exists. It is important to note the difference in scales of the two figures. This reflects both the higher flows and lower transport distances in the Afon Cyff.

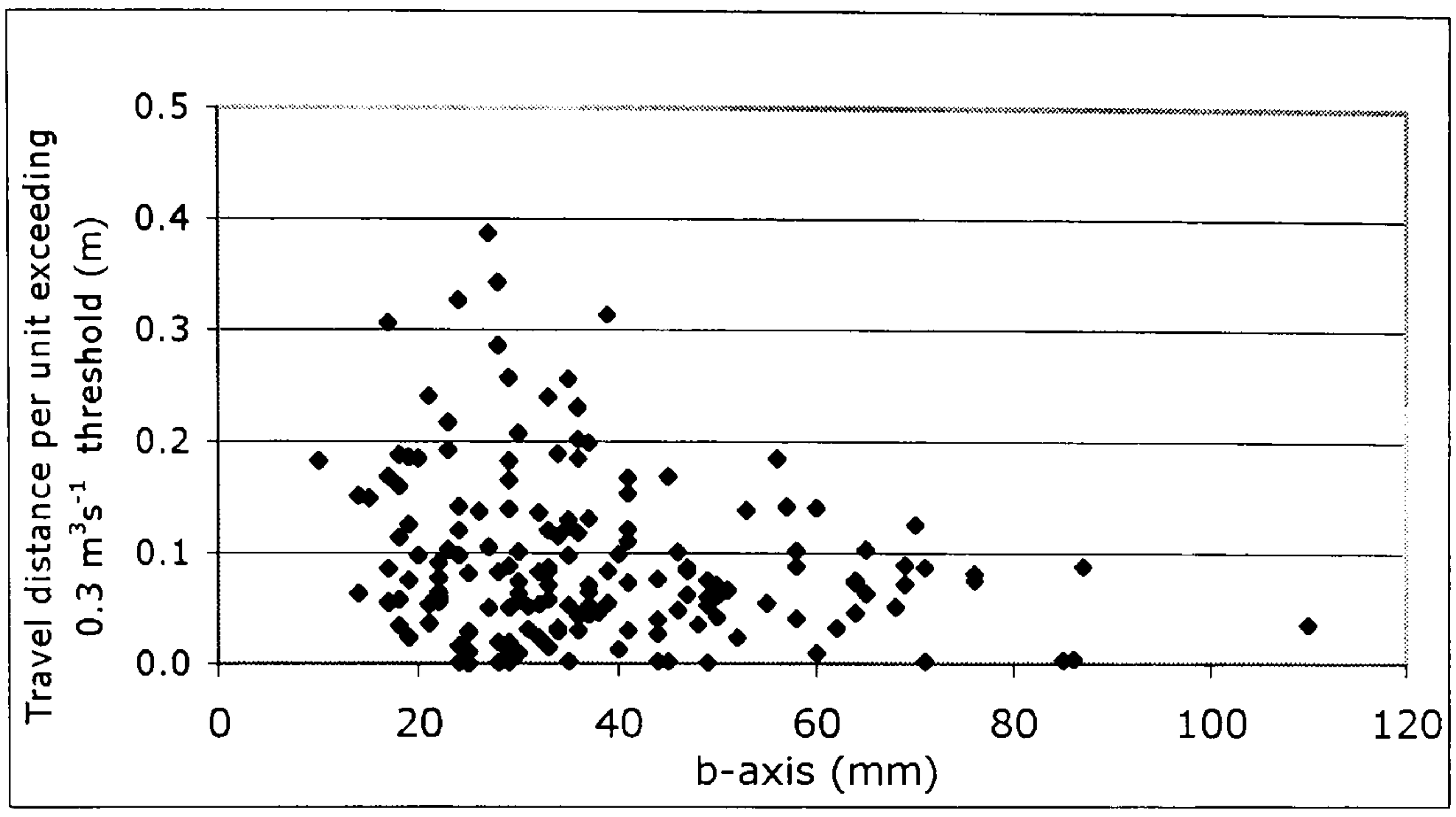


Figure 4.29. Total travel distance of individual clasts compared to b-axis in Nant Tanllwyth

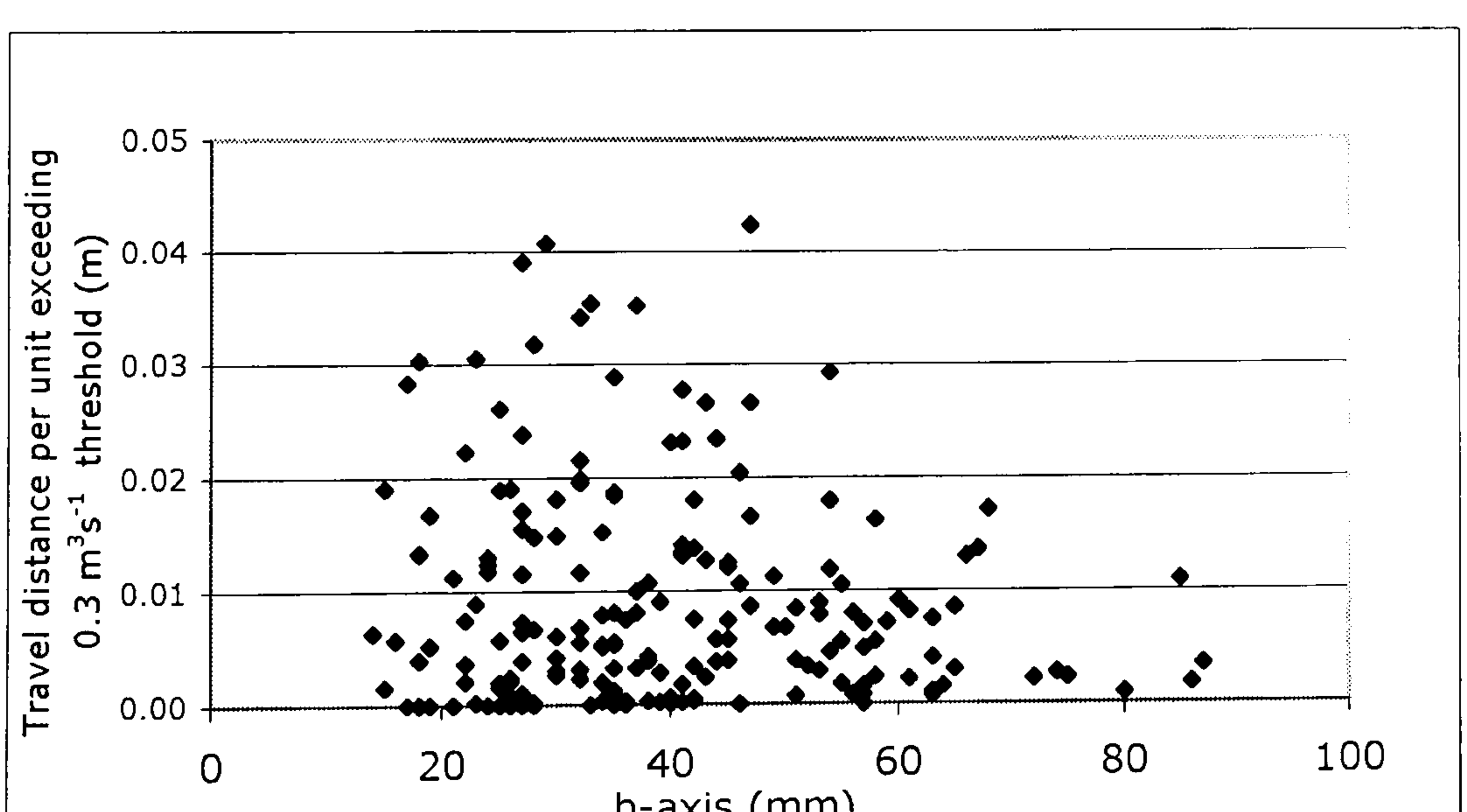


Figure 4.30. Total travel distance of individual clasts compared to b-axis in Afon Cyff

All four charts show an approximate envelope in which values are maintained. Visual analysis of the b-axis data suggests maximum travel distances that peak in the 22-32 mm size range in both channels. However, the small end of the size range is truncated due to the physical limit in the size of tracers that could be implanted into a magnet without breakage. The fact that the peak is not in the smallest particles might initially suggest a hiding mechanism might be operating. With no problems existing in tagging larger clasts, a clear reduction in travel distance with increasing size is seen. The few tracers in the large size fraction are clearly limited in their travel distance.

By grouping the data, as done by Hassan *et al.* (1991), a clearer pattern emerges; this is shown in Figure 4.31, showing that mean distance moved progressively decreases with size fraction.

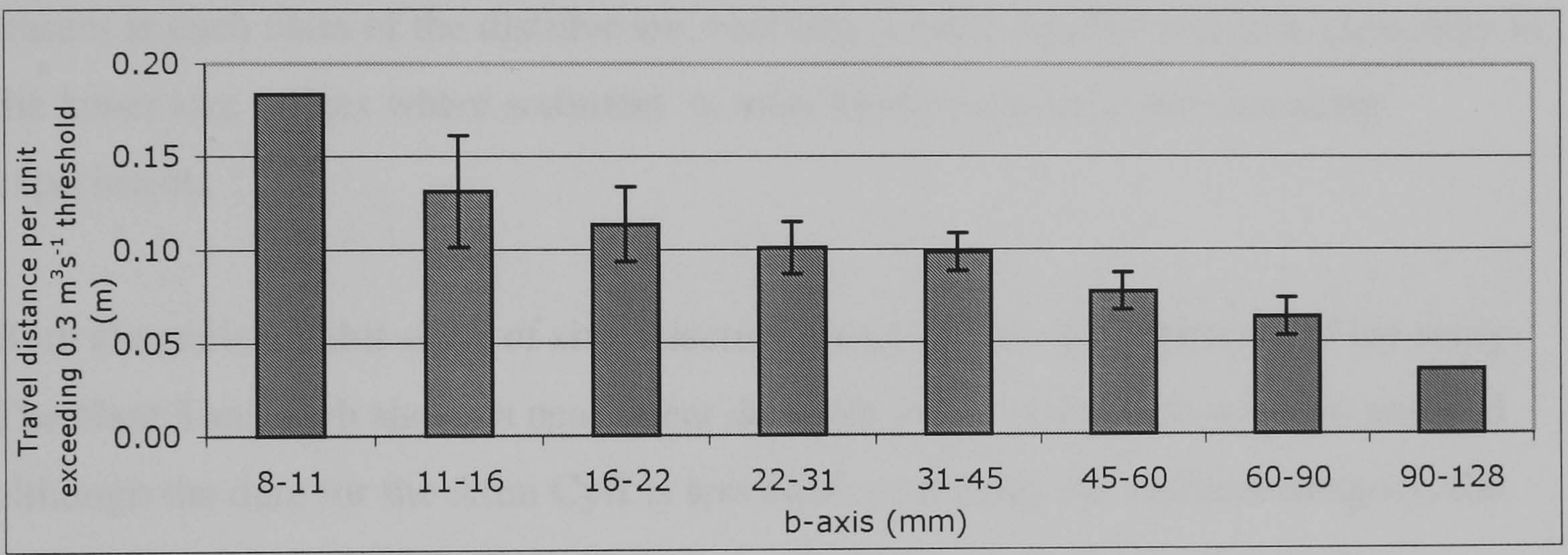
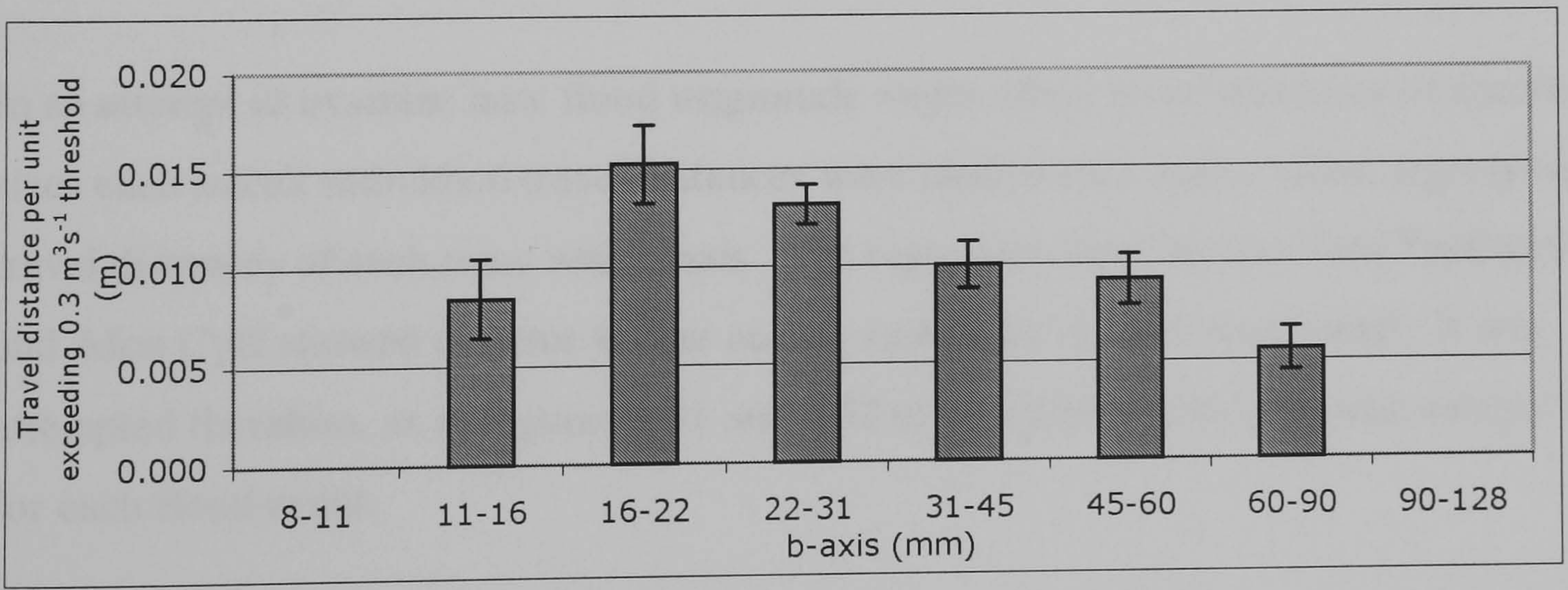


Figure 4.31. Mean travel distance of tracers by half phi-size fraction in the Nant Tanllwyth



**** Note differences in scales of y-axes between Nant Tanllwyth and Afon Cyff charts***

Figure 4.32. Mean travel distance of tracers by half phi-size fraction in the Afon Cyff

After grouping the data into half phi-size classes (and calculating means of particle travel distance), there is a smooth transition between smaller particles travelling further, and larger clasts shorter distances in the Nant Tanllwyth. In the Afon Cyff, the smallest particles do not move as far as the next four larger categories. The peak shown in the 8-11 mm class in the Nant Tanllwyth (Figure 4.31) is partly attributable to a peak travel distance of an individual tracer and does not represent a true mean. This highlights a deficiency in the initial tracer selection procedure, where a greater number of tracers might have yielded statistically more significant results at the tails of the distribution. This is further highlighted by the inability to express full standard error bars at the tails of the distribution. Indeed work by Wathen *et al.* (1998) used an equal number of tracers in each class of the distribution, enabling a more detailed analysis, especially in the lower size ranges where sediment is more likely to become lost in tracing experiments

Both channels exhibit signs of size selective transport over the timescale of the study. The Nant Tanllwyth shows a near linear decrease in travel distance with phi size and although the date for the Afon Cyff is less clear, excepting the smallest category, the grouped data show larger clasts are universally transported shorter distances.

ANALYSIS BY INDIVIDUAL FLOOD EVENT

In an attempt to examine how flood magnitude might affect travel distances of specific sizes each trace's individual travel distances were plotted on a scatter chart, regressing travel distances of each trace with b-axis. The regression lines for the Nant Tanllwyth and Afon Cyff showed extreme scatter and no significant results were found. It was attempted therefore, as in Figures 4.31 and 4.32 to group the tracers into size categories for each flood event.

Figures 4.33 and 4.34 show the mean travel distance of each size class, for each trace in the Nant Tanllwyth and Afon Cyff respectively. Data for these graphs were allocated from the raw dataset with no backfill, as backfill would destroy the validity of individual trace and tracer results. With the removal of a significant amount of data, size categories are in phi, rather than half phi categories.

Data are ordered by magnitude of flood event for each study period, with magnitude measured by total flow exceeding 0.3 m^3s^{-1} during the study period.

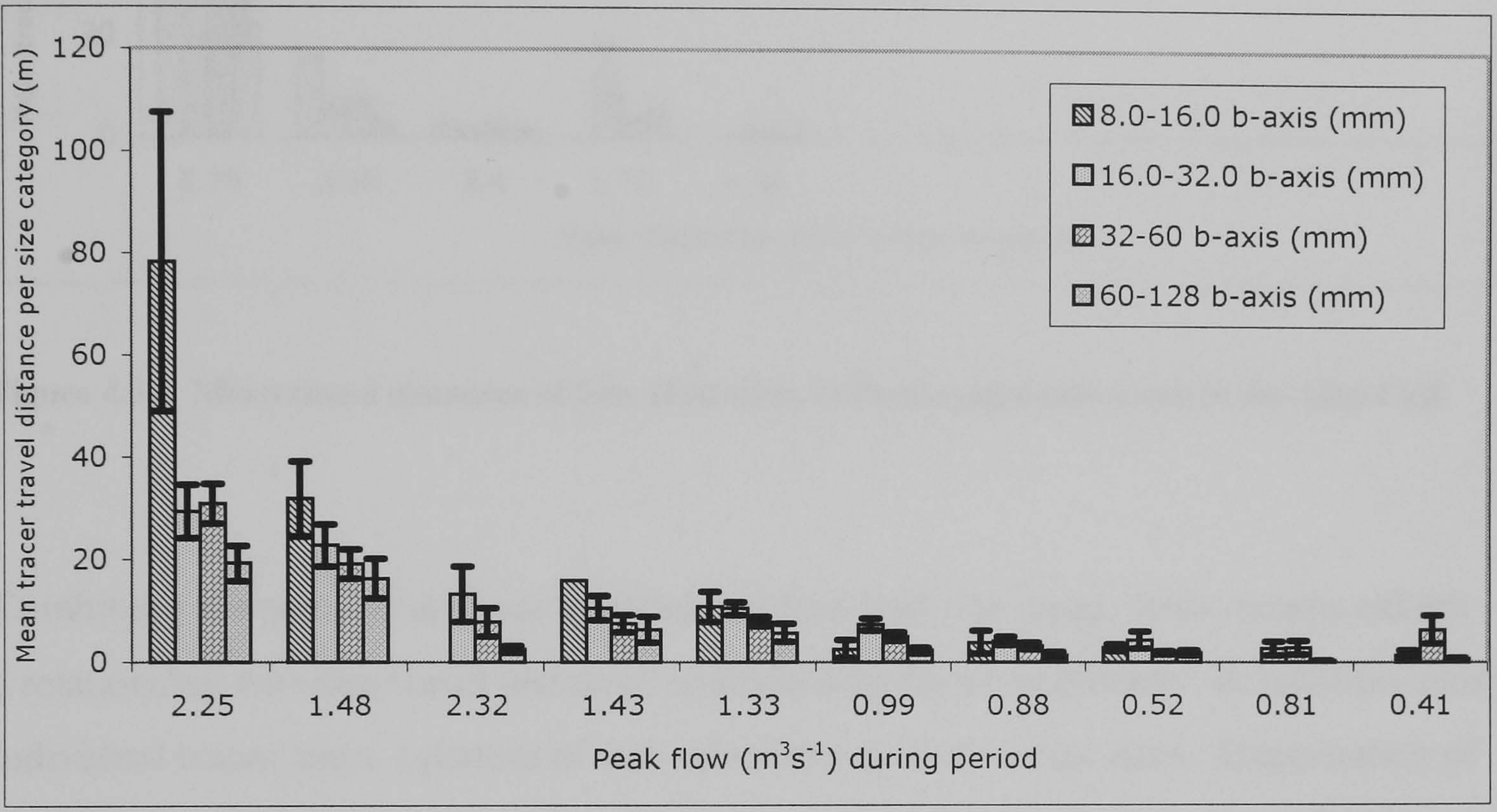


Figure 4.33. Mean travel distances of four clast sizes, in flood magnitude order in the Nant Tanllwyth.

Only trace 1 (2.32 m^3s^{-1}) is out of synchrony in the figure and this trace had a small number of tracers in the channel.

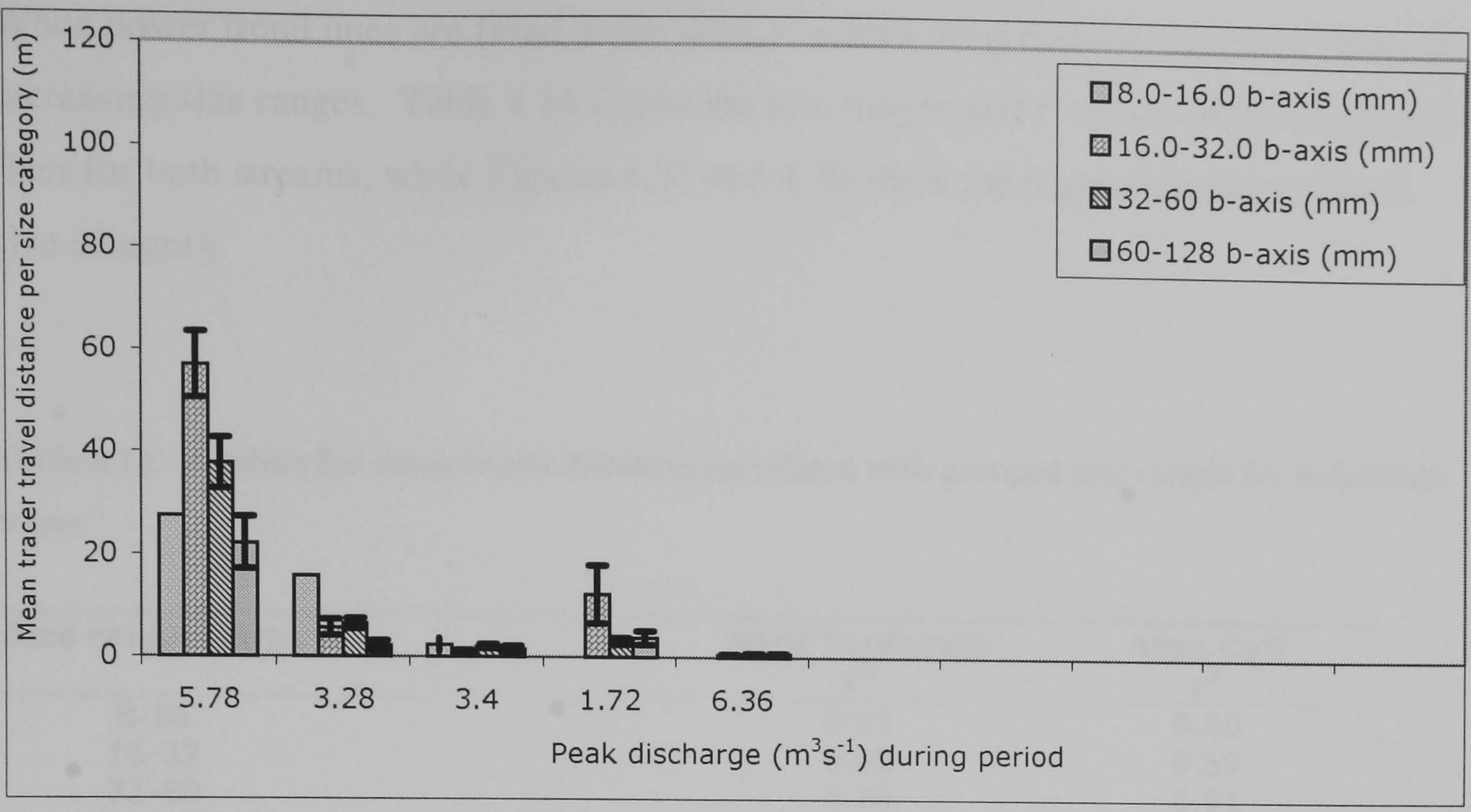


Figure 4.34. Mean travel distances of four clast sizes, in flood magnitude order in the Afon Cyff

Combining elements of analysis by threshold flow and size range, both streams exhibit a relationship between travel distances controlled by flood magnitude. In addition, most individual traces show a pattern of size selectivity between class sizes. Examination of the Nant Tanllwyth data shows that small size ranges in particular, are controlled by flood magnitude. The size selectivity clearly shown when examining all tracers throughout all traces, does not exhibit itself as clearly within individual traces. During the larger 5 flood events in the Nant Tanllwyth, size selection is more prevalent than in the lower order floods. There is little overall exception to the trend, apart from trace 1, where smaller travel distances are noted. The seeding of all tracers before trace 1 is to be noted when interpreting this result.

In the Afon Cyff, fewer traces make meaningful analysis more difficult. However, data are available for the three size ranges between 16 and 128 mm. There is significantly more scatter in the plots than in the Nant Tanllwyth, with travel distance based on flood magnitude also less clear. Although during the trace containing greatest number of peak flows all size ranges are transported furthest, notable variation takes place during smaller flooding periods. There is particular variation in the 16 - 32 mm size fraction, where a high mean distance (though with large variation) is seen during trace 5.

When power trend lines are fitted to the data, r^2 values progressively decreased through increasing size ranges. Table 4.14 shows the size ranges and r^2 values of the regression lines for both streams, while Figures 4.35 and 4.36 show the regression lines of each size category.

Table 4.14. r^2 values for mean travel distances correlated with grouped size ranges for individual traces

Size range (mm)	Nant Tanllwyth r^2	Afon Cyff r^2
8-16	0.91	0.80
16-32	0.85	0.59
32-60	0.79	0.91
60 - 128	0.75	0.71

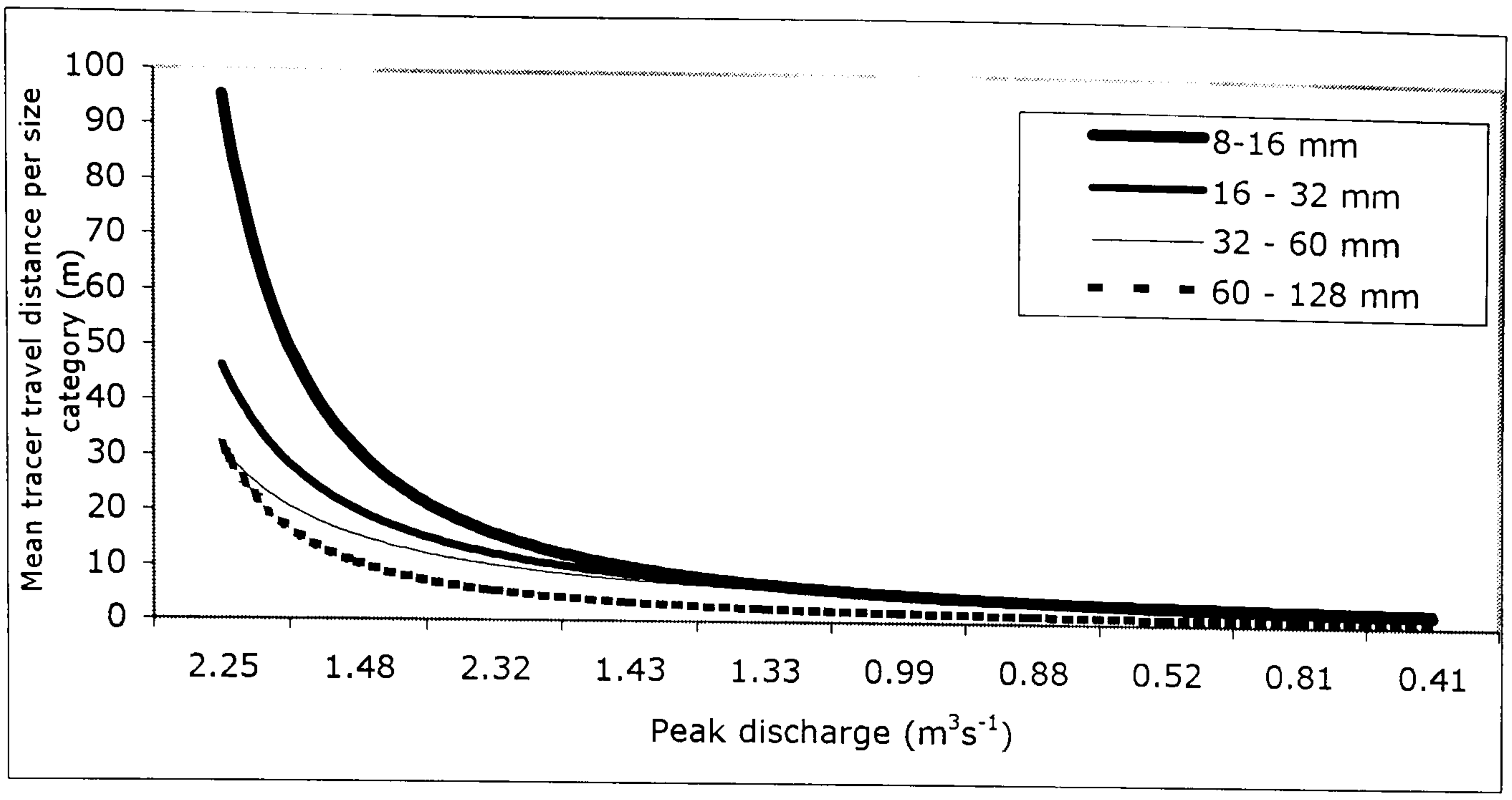


Figure 4.35. Regression lines of mean travel distances of grouped size ranges for individual traces in the Nant Tanllwyth

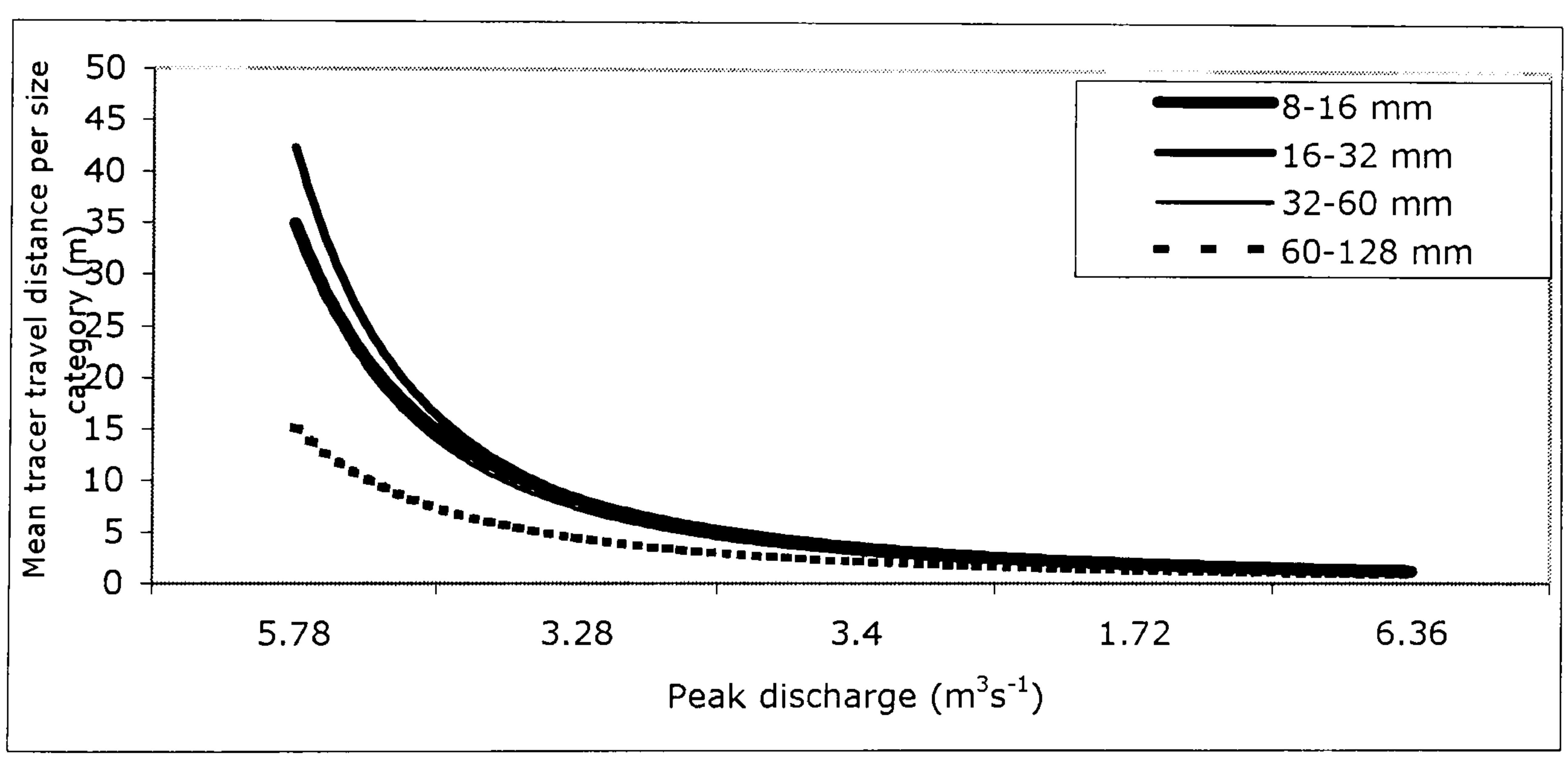


Figure 4.36. Regression lines of mean travel distances of grouped size ranges for individual traces in the Afon Cyff

The fitted regression lines show more clearly the variation in transport regimes within the Nant Tanllwyth and Afon Cyff. Whilst in the Nant Tanllwyth the difference in the transport between each size fraction is increased during high flow periods, with the Afon Cyff, only the largest of the size ranges shows significantly lower transport rates through the traces. In this channel, the three smaller size ranges show little divergence through flood sizes.

4.3.4. Analysis of flux by shape

The inherent difficulty in investigating the effects of shape on tracer transport lies in the fact that there is so much variation in the shapes of natural clasts in the channel. With the shale of Plynlimon not being resistant to long term abrasion, most clasts are angular and poorly rounded. Using Zingg analysis (Zingg, 1935), few if any spherical forms exist and the bulk of rods seem easily to be easily broken into smaller pieces. Blades and discs dominate the clastic mix. The shape distributions are shown in section 1.6.2. It is also extremely difficult to isolate shape and remove the effects of size on travel distance without using manufactured and standardised tracers. This is especially true with such a large size distribution and only limited number of tracers available. The problem of isolating shape is partially solved by using manufactured tracers of specified shape and size categories, as shown by Warburton and Demir (in press). However, this approach was not applicable in the scope of this project.

All presented figures and tables have, unless stated otherwise been extracted from travel distances made dimensionless through dividing by the standard threshold flow. Only total travel distances of all tracers are considered, with shape seen as secondary to size in terms of subtle effects of forest operations. Changes in transport of shape classes were not examined in terms of the two phases of forestry.

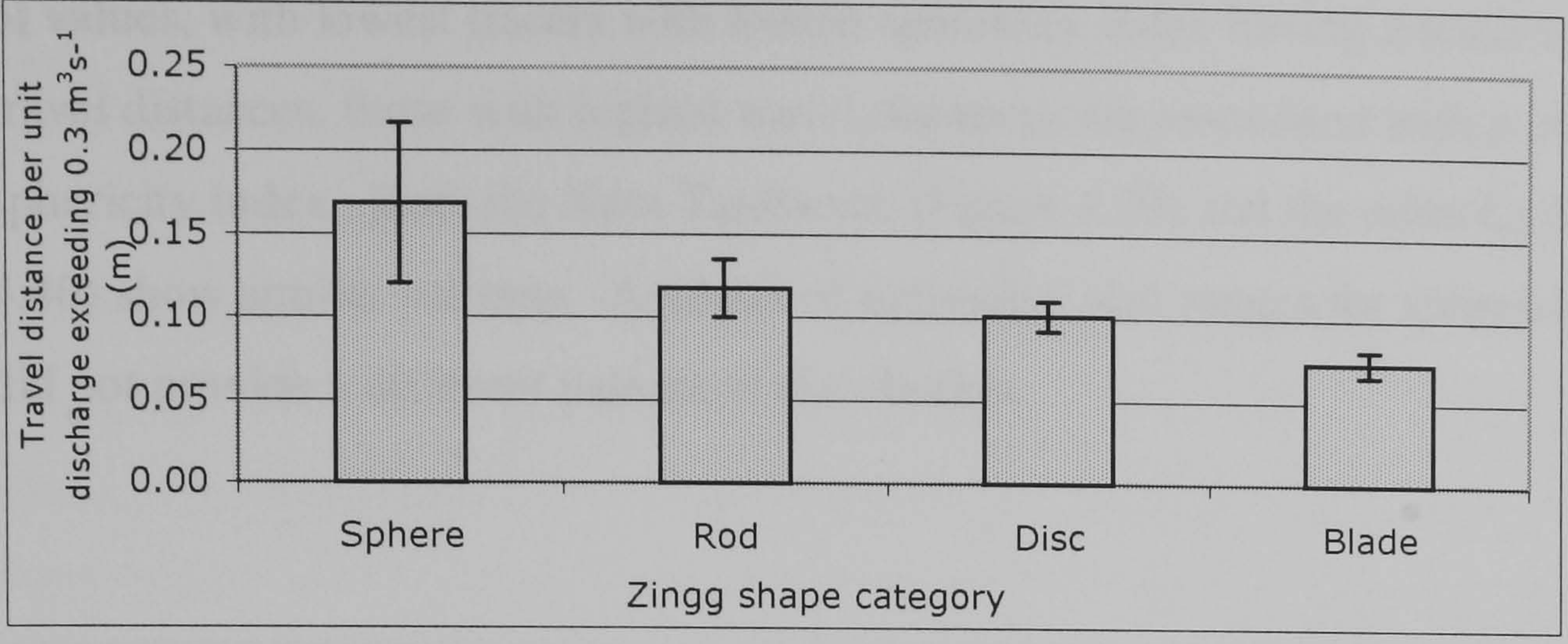


Figure 4.37. Relationship between shape class and mean movement per day in Nant Tanllwyth

Both channels show differences in travel distances based on shape. Spheres move on average the furthest in the Tanllwyth, but in the Afon Cyff travel shorter distances than rods or discs. This variation can be attributed to the large error involved due to the small number of spheres in the sample.

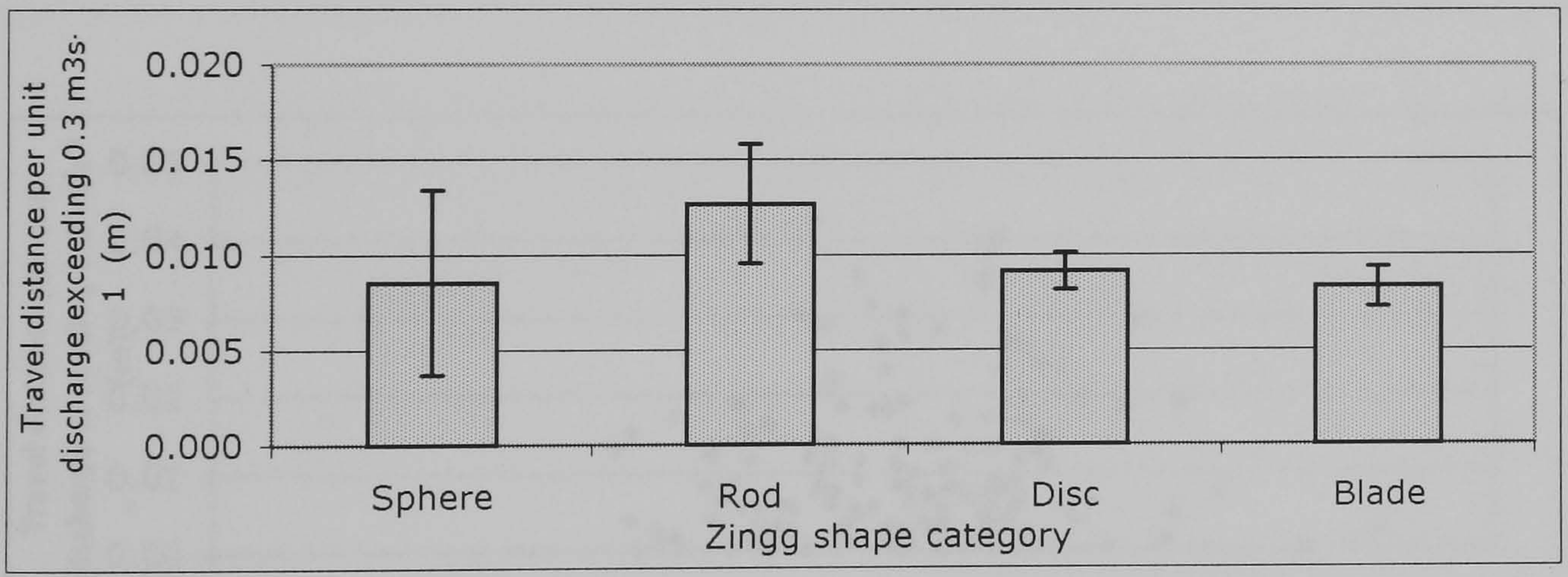


Figure 4.38. Relationship between shape class and mean step movement per day in Afon Cyff

Examining the effects of sphericity (Krumbein, 1942) shows an approximate envelope of values, with lowest tracers with lowest sphericity index having a tendency for lower travel distances, those with highest travel distances are associated with a mid to highest sphericity index. Both the Nant Tanllwyth (Figure 4.39) and the Afon Cyff (Figure 4.40) show similar patterns. Analysis of individual size ranges for sphericity and shape did not provide a different pattern of distribution.

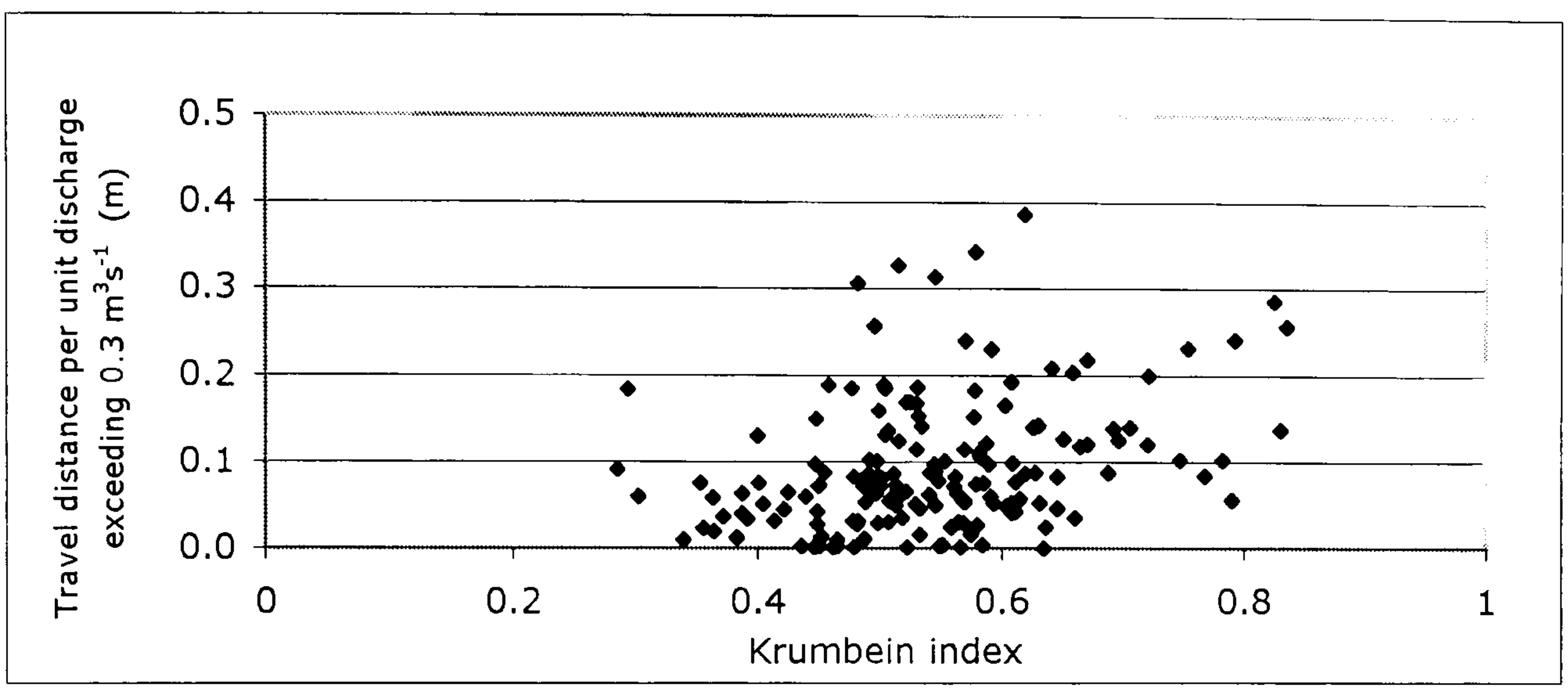


Figure 4.39. Mean travel distance per day based on Krumbein index in the Nant Tanllwyth

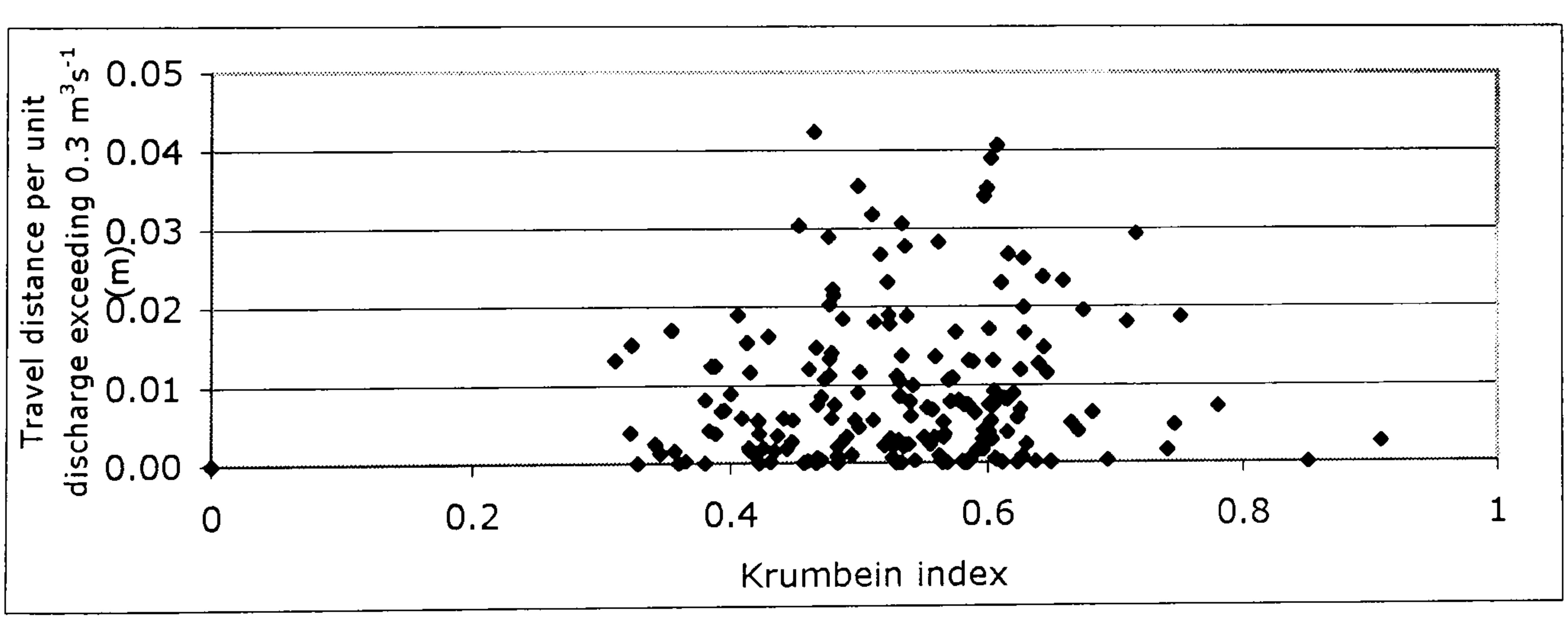


Figure 4.40. Mean travel distance per day based on Krumbein index in the Afon Cyff

4.3.5. The effect of burial depth

In both channels, travel distances were examined with reference to burial depth (Hassan, 1990) and channel position (Gomez, 1984) of clasts in the two channels. Burial depths of recovered clasts averaged in excess of 0.05 m and some clasts were recovered from as deep as 0.5 m. Analysis was made of each clast travel distance and probability of entrainment compared to its original burial position recorded on the previous trace. Furthermore, analysis was made by grouping tracers into 0.05 m burial depth categories and clast size categories. No relationship was found for any trace, nor was there a distinctive pattern between grouped burial depth classes. This suggests that once the threshold of transport is reached, the active layer becomes mobile and all clasts have an equal probability of being entrained. This is subtly different from true equal mobility where the distance the particle moves is the subject of the probability function. There appears to be a " moving mat" in the two rivers where once a threshold of flow is crossed, the mat becomes active, at which point preferential transport of smaller particles occurs.

Four examples (figures 4.41 - 4.44) from traces six and seven are shown that demonstrate the variation in tracer travel distances based on water and burial depth. Indeed trend lines from subsequent traces show opposite relationships, though there is clearly no direct relationship between the variables to draw conclusive trend lines. Other traces showed similar variation and analysis of grouped data showed weak results.

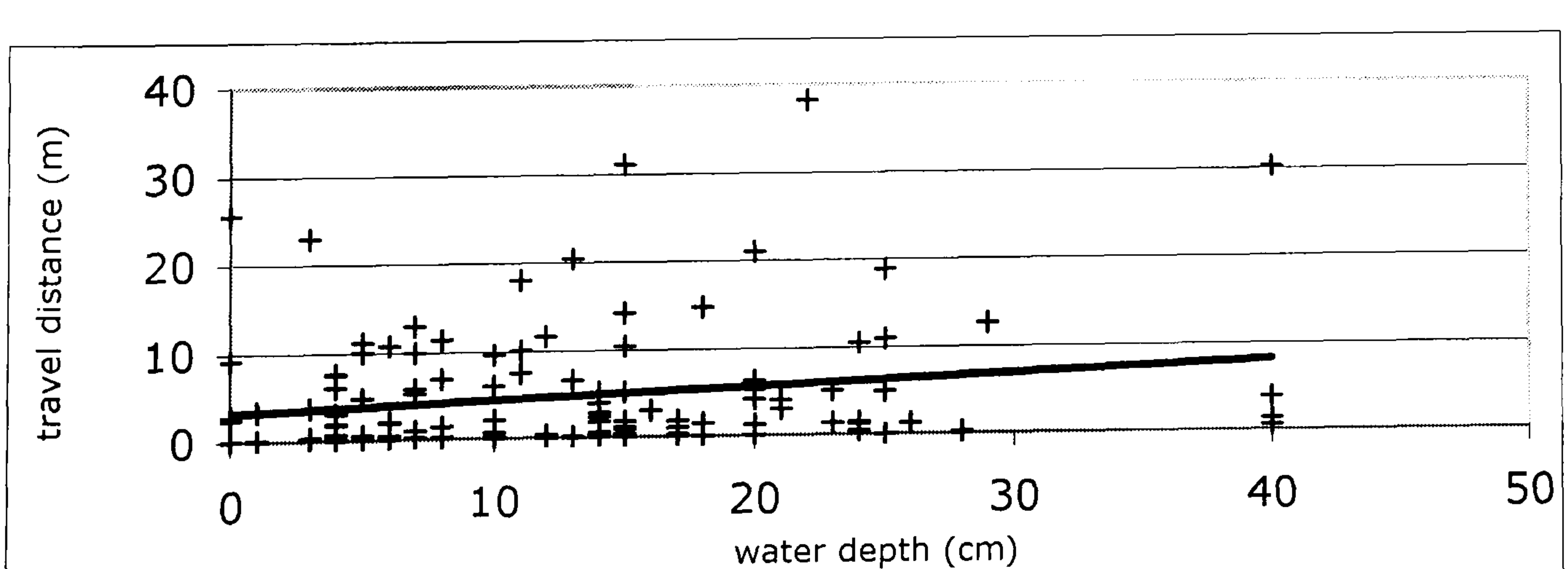


Figure 4.41. Travel distances of trace 6 based on water depth of previous trace

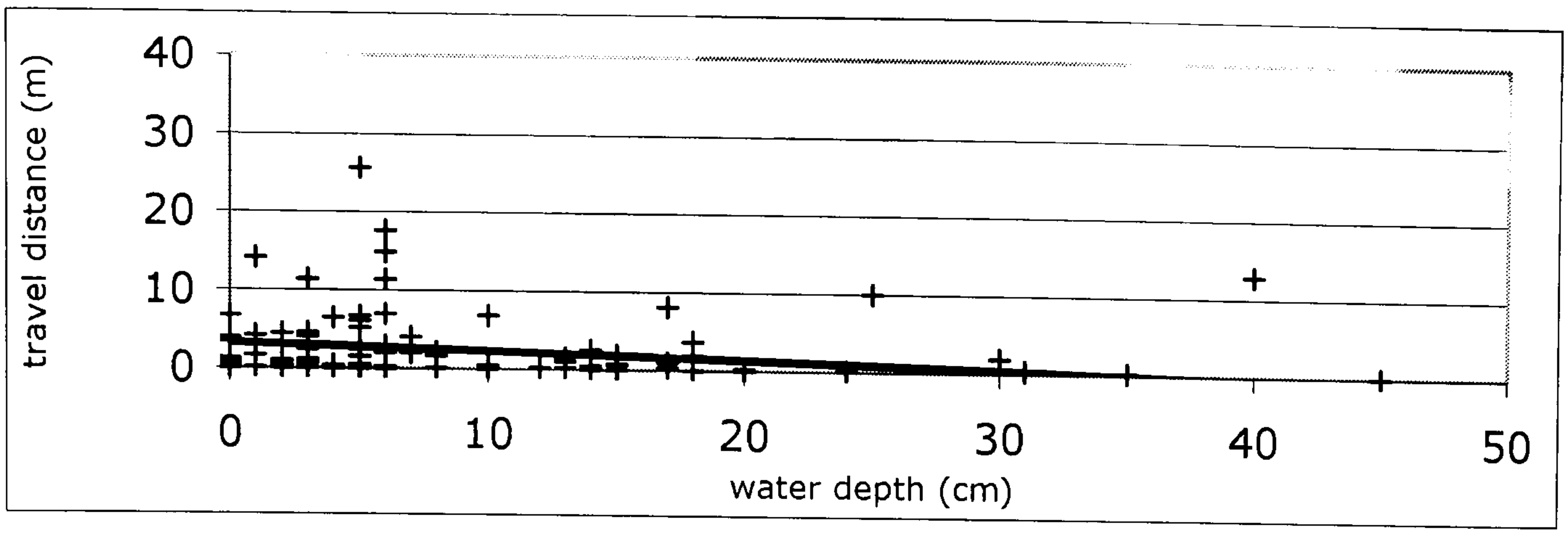


Figure 4.42. Travel distances of trace 7 based on water depth of previous trace

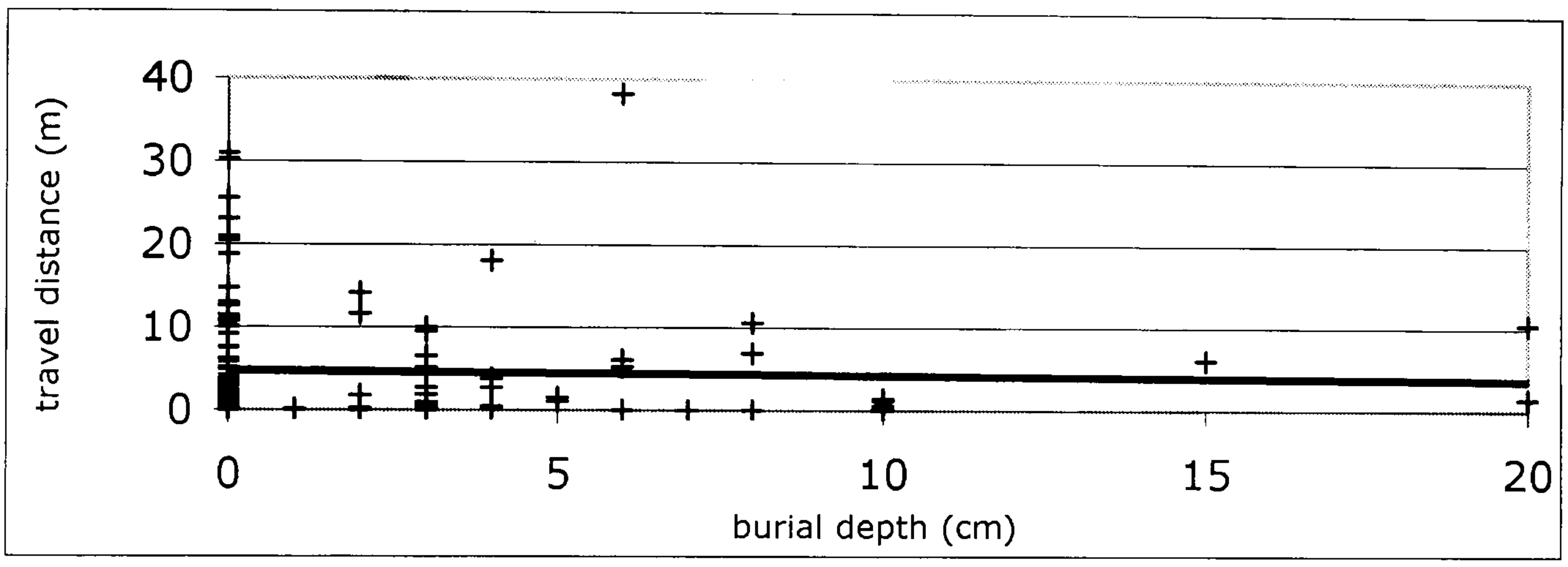


Figure 4.43. Travel distances of trace 6 based on burial depth of previous trace

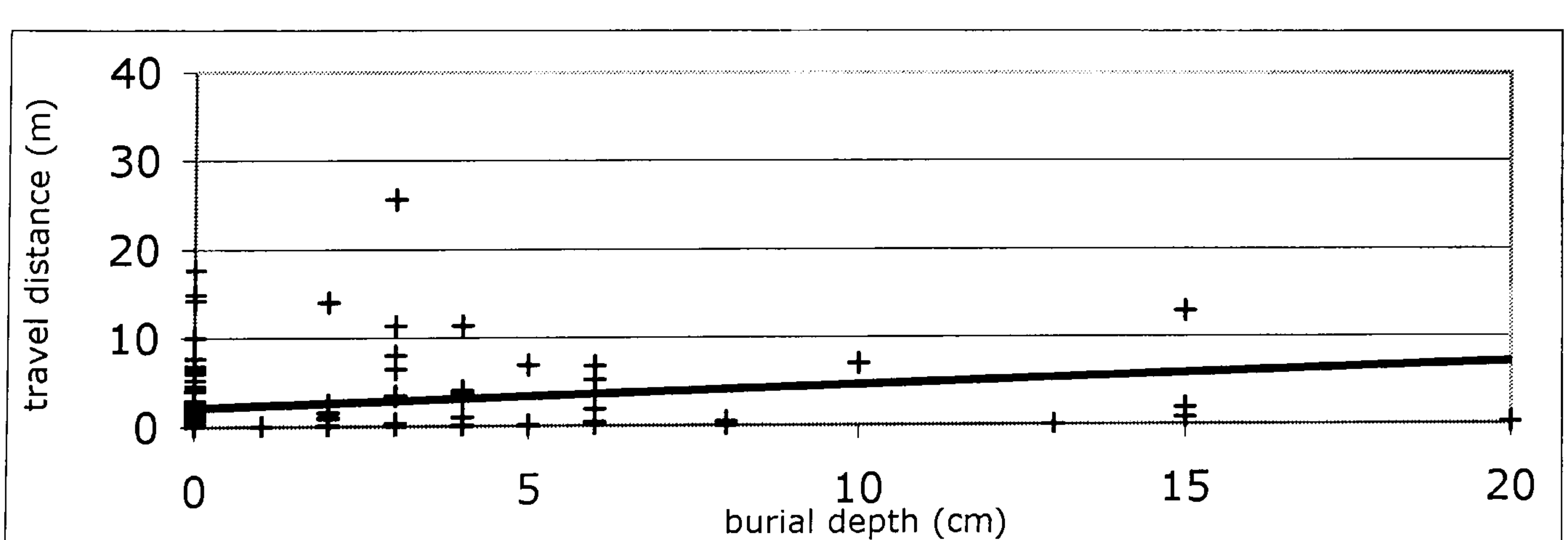


Figure 4.44. Travel distances of trace 7 based on burial depth of previous trace

4.4. Abrasion of tracer clasts

Introduction

Analysis of clast abrasion was carried out by determining the mass of tracers after the tracing programme was completed in June 1997 and clasts were removed from the channels and returned to the laboratory. Reference should be made to the appendices where a copy of the paper Stott and Sawyer (1999) is attached.

Results

Table 4.15 shows summary statistics for all Tanllwyth and Cyff tracers. Though tracers in the forested Nant Tanllwyth channel appear to show higher weight losses than those in the Afon Cyff, the difference is not statistically significant when compared using the *t*-test. The mean mass of all tracers introduced to the channels was 78.51 g and so this represents an actual mean weight reduction of 2.74 g per clast per year.

Table 4.15. Summary statistics for tracer abrasion (% weight loss) and travel distances for Tanllwyth and Cyff channels

	n	Annual mean % weight loss	Max % weight loss
Cyff tracers	114	2.8 ± 0.2	42.2
Tanllwyth tracers	114	4.2 ± 0.2	57.2
All tracers	228	3.5 ± 0.1	57.1
Blades	95	2.8 ± 0.2	24.5
Discs	110	3.8 ±0.2	42.2
Spheres	4	1.2 ± 0.4	2.5
Rods	19	5.4 ± 0.7	57.2

Table 4.15 also shows the variations in both weight loss and travel distance for clasts in the four Zingg shape classes. Rod shaped clasts showed the greatest weight losses (5.4 ± 0.7 %) and the difference between the weight loss of rods and blades is significant ($p < 0.05$) as shown by the *t*-test. The greater weight losses of rod shaped clasts may be

accounted for by their higher travel rates. The low number of spheres in the sample means that estimates of weight loss and travel distance are unreliable.

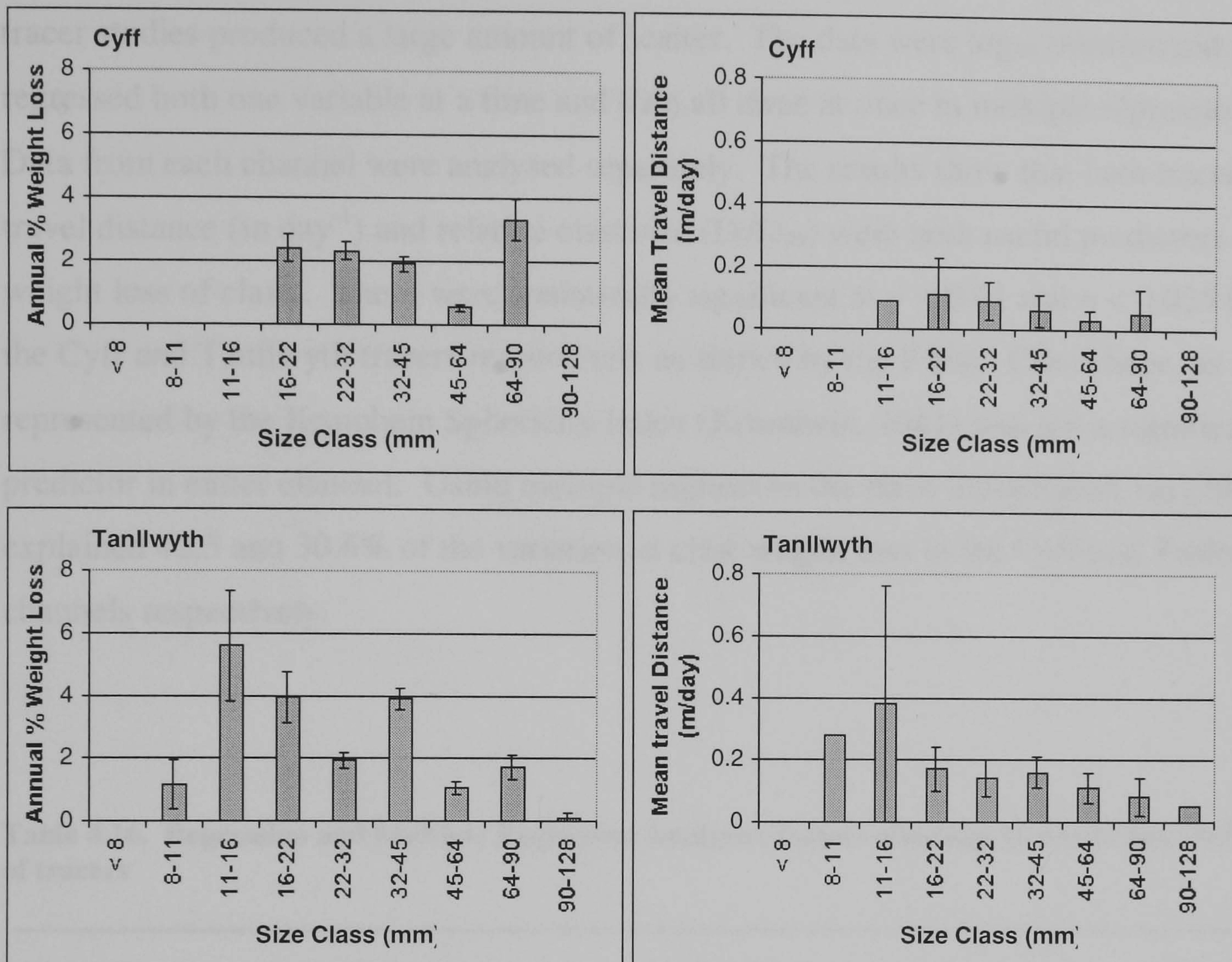


Figure 4.45. Analysis by size: weight loss of tracers and distance travelled for Tanllwyth and Cyff tracers

Figure 4.45 shows mean annual weight losses for tracers by their size class. When all tracers are combined, the trend appears to show greatest weight losses in the 11-16 mm and 16-22 mm size classes with a decrease in weight loss in the larger size classes. However, the small sample size in the 11-16 mm class (n = 4) means estimates are unreliable. The only statistically significant differences between mean weight loss and clast size class was found in the coarser size classes. Weight loss in the 32-45 mm class was significantly greater than in the 45-64 mm class ($p < 0.01$) and weight loss in the 45-64 mm class was significantly lower than in the 64-90 mm class ($p < 0.05$).

REGRESSION AND MULTIPLE REGRESSION ANALYSIS

The results of regression and multiple regression analysis are presented in Table 4.16. Data were plotted for each channel separately and in common with many previous tracer studies produced a large amount of scatter. The data were $\log_{10}$ transformed and regressed both one variable at a time and then all three at once in multiple regression. Data from each channel were analysed separately. The results show that both tracer travel distance (m day^{-1}) and relative clast size (D_i/D_{50}) were both useful predictors of % weight loss of clasts. These were statistically significant at $p < 0.01$ and $p < 0.025$ for the Cyff and Tanllwyth tracers respectively as shown by the F test. Clast shape, as represented by the Krumbein Sphericity Index (Krumbein, 1941) was not a significant predictor in either channel. Using multiple regression the three independent variables explained 42.5 and 30.6% of the variation in clast weight loss in the Cyff and Tanllwyth channels respectively.

Table 4.16. Regression and Multiple Regression Analyses: factors affecting % weight loss (%WL) of tracers

	CYFF	Multiple R	v_1	v_2	F	Significance
	Regression					
1	Log_{10} %WL vs. Log_{10} distance	31.6	1	77	8.45	$p < 0.01$
2	Log_{10} %WL vs. Log_{10} sphericity	14.5	1	77	1.64	n.s.
3	Log_{10} %WL vs. Log_{10} D_i/D_{50}	33.2	1	77	9.46	$p < 0.01$
	Multiple Regression					
4	Log_{10} %WL vs. Log_{10} distance, Log_{10} sphericity, Log_{10} D_i/D_{50}	42.5	3	77	5.43	$p < 0.01$
	TANLLWYTH					
	Regression					
5	Log_{10} %WL vs. Log_{10} distance	22.9	1	105	5.79	$p < 0.025$
6	Log_{10} %WL vs. Log_{10} sphericity	10.1	1	105	1.08	n.s.
7	Log_{10} %WL vs. Log_{10} D_i/D_{50}	21.9	1	105	5.28	$p < 0.025$
	Multiple Regression					
8	Log_{10} %WL vs. Log_{10} distance, Log_{10} sphericity, Log_{10} D_i/D_{50}	30.6	3	105	3.50	$p < 0.025$

v_1 and v_2 are upper and lower d.f respectively.

Further investigation into how clast shape and size affect tracer travel distance is shown in Table 4.17. The proportion of variation in travel distance explained by sphericity and relative grain size (D_i/D_{50}) is maximised to 30.9 and 32.3% in the Cyff and Tanllwyth respectively by dividing sphericity by relative size to remove the effect of size. This suggests that clast shape (sphericity) does have a significant effect on travel distance after allowing for size ($p < 0.001$).

Table 4.17. Regression analysis results of factors affecting tracer travel distance

	Regression	R	v_1	v_2	F	Significance
	CYFF					
1	Distance vs. sphericity	2.6	1	118	0.08	n.s.
2	Distance vs. Di/D_{50}	27.1	1	118	9.26	$p < 0.01$
3	Distance vs. (sphericity / D_i/D_{50})	30.9	1	118	12.34	$p < 0.001$
	TANLLWYTH					
4	Distance vs. sphericity	21.5	1	164	7.91	$p < 0.01$
5	Distance vs. Di/D_{50}	24.6	1	164	10.58	$p < 0.01$
6	Distance vs. (sphericity / D_i/D_{50})	32.3	1	164	18.98	$p < 0.001$

v_1 and v_2 are upper and lower d.f respectively.

4.5. Summary

The data presented has shown that total bedload output and individual sediment flux is significantly higher in the forested Nant Tanllwyth than in the open moorland Afon Cyff catchment, despite significantly lower flow levels. It has also been established that the relationship between flow thresholds and bedload outputs is better in the Nant Tanllwyth than the Afon Cyff. During and after the period of timber harvesting in the Nant Tanllwyth, total bedload outputs monitored using bedload trapping did not show any significant change. Using magnetic tracers to represent the particles on the channel bed, mean travel distances of individual clasts did increase significantly after the felling period. Tracers also showed that travel distance of clasts was controlled by the size of the clast, with tracers in the smallest size ranges moving the furthest distance. Surprisingly, burial depth was not found to be an important factor influencing particle travel distance.

Section 5: Discussion

5.1. Introduction

This study has attempted to examine the nature of sediment transfer in a small upland stream with a forested catchment. It has compared this to transfer in the nearby Afon Cyff catchment. Furthermore, by studying the mechanisms of coarse bedload transport, the effects of ecologically sensitive plot-scale timber harvesting of 20 % of the Nant Tanllwyth catchment have been examined.

The discussion will consider the study from two directions. The first relates to study methodology, addressing how the experiment measured the mechanics of bedload transport though the fluvial systems of the Nant Tanllwyth and Afon Cyff. The second part addresses how forestry has affected the transport and production of coarse sediment and considers the likely future management implications.

The discussion will examine the results presented in section 4, and has four main aims:

1 To suggest explanations for the results described in section 4;
2 to place and relate these results in the context of previous work described in section 2;
3 to appraise how the study methodology described in section 3 provides an insight into the effects of forestry on bedload transport processes, and
4 to suggest the direction of further work in the field.

5.2. Bedload transport: the monitoring programme

The analysis will deal firstly with bedload trap results and secondly with individual tracer dynamics. Discussion of how the techniques may be drawn together is given in section 5.2.3.

5.2.1. *Bedload trapping: design, monitoring and results*

Bedload trapping methodology is given in section 3.4, with results shown in section 4.2. This section aims to suggest reasons for these results and to place the results into the context of previous trapping work in the Plynlimon catchments.

DATA QUALITY ISSUES

Before interpreting the results of the bedload trap data, what data were actually being collected must be considered. The issue of trap efficiency is not considered in Moore and Newson (1986) to which significant reference is made later in the discussion. It is deemed imperative to consider it before discussion of the results is undertaken. The function of the end of the channel bedload traps is to monitor coarse sediment outputs that can not be covered by suspended sediment observation techniques. The traps are situated at a sampling point in the catchment to examine activity above the traps. Suspended sediment outputs during 1996 in the catchments (Stott and Marks, 1998) were 24.2 t km^2 yr^{-1} for the Nant Tanllwyth and 5.3 t km^2 yr^{-1} for the Afon Cyff. Analysis of bedload trap material however shows that up to 30 % of the sediment is in the size range that would typically be transported in flood as suspended sediment. This sediment is directly sampled during flood events (the suspended sediment sampler is located in the flow above the bedload trap) and therefore the sediment might conceivably be sampled twice. It is difficult, therefore, to accurately combine the results for suspended sediment with that of the bedload trap at this stage, as it is impossible to quantify this possible error. It can however be assumed that the bedload trap does collect the coarse sediment output of the channel. This assertion can be made as observations below both traps revealed little coarse sediment immediately below the lower wall of the pond. However, as discussed in earlier chapters, there were slight differences between the Afon Cyff and Nant Tanllwyth bedload traps. The Nant Tanllwyth is built on a straight section where there are no major complex flow structures affecting the entrance to the trap in high flood levels. Deposits were found to be relatively even within the trap, illustrated in Figure 5.1 below which shows the sediment surface of the Nant Tanllwyth bedload trap on 5th October 1996. The vertical axis shows the depth below the horizontal measurement datum; flow is travelling from front right to back left. Mechanisms of deposition can be seen from the figure to deposit first at the entrance lip of the trap, then force sediment forward towards (but not over top) the exit lip of the trap. On no occasion did the sediment height in the trap come within 0.3 m of the exit lip. Analysis of the changes in the surface of the bedload trap was undertaken by examining the changes of each of the 144 measurement nodes. This technique proved useful, though no technique (apart from tracers in conjunction with total change, by literally entering tracers in the bedload trap) is able to properly distinguish between deposition and redistribution.

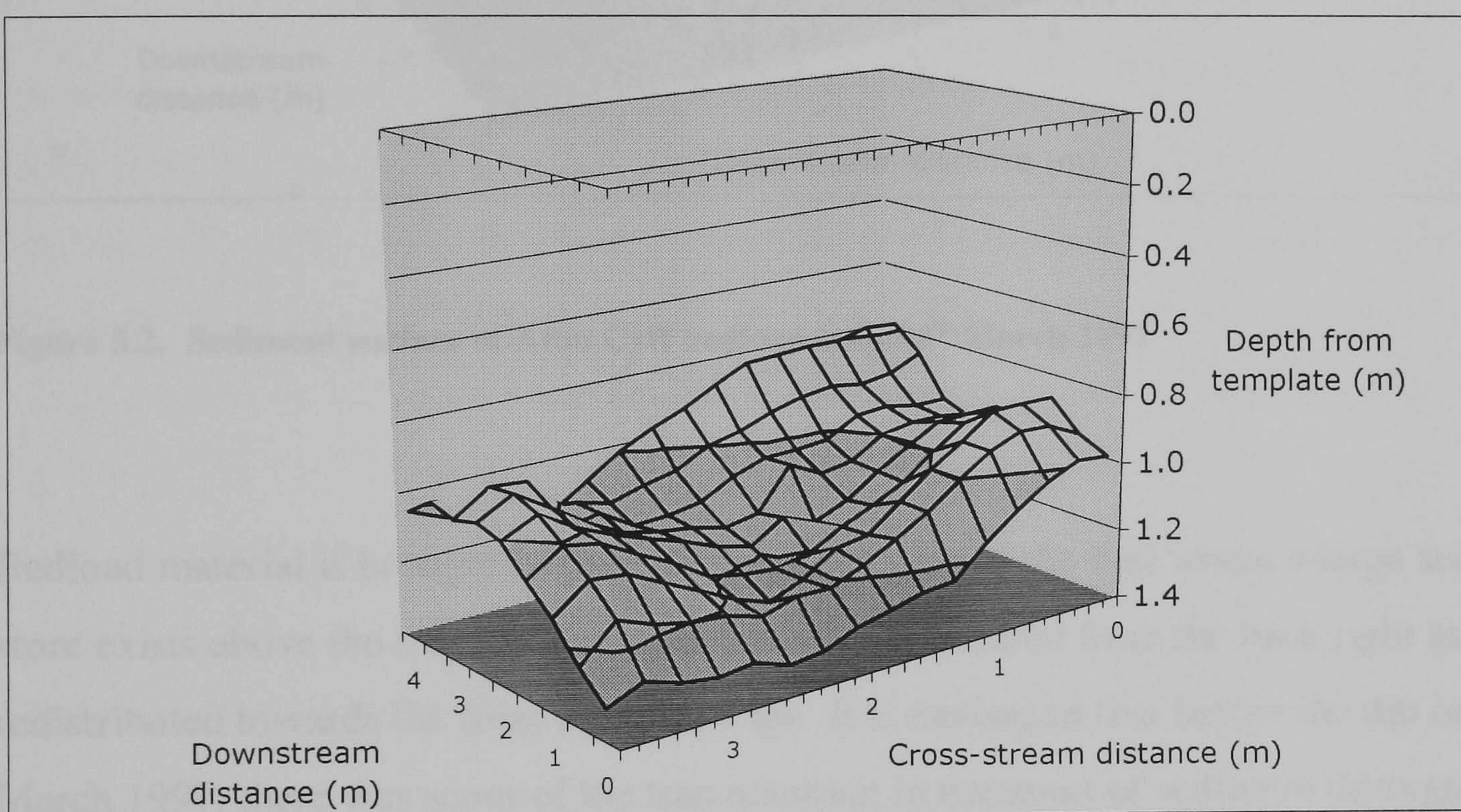


Figure 5.1. Sediment surface of Nant Tanllwyth bedload trap on 5th November 1996

In contrast to the Nant Tanllwyth, the bedload trap in the Afon Cyff experienced a more complex flow structure (especially during high flows) at its upstream lip. The construction of the trap on a bend in the channel and in an area of low bedslope (and hence low stream velocity) has resulted in ponding and forced sedimentation to occur upstream. Nearly all tracers at the end of the Afon Cyff experimental section were found in this area of sedimentation. The bedload trap is itself affecting the bedload transport characteristics of the stream in a way not occurring in the Nant Tanllwyth. A surface profile of the Afon Cyff bedload trap is shown below, taken from 14 March 1997.

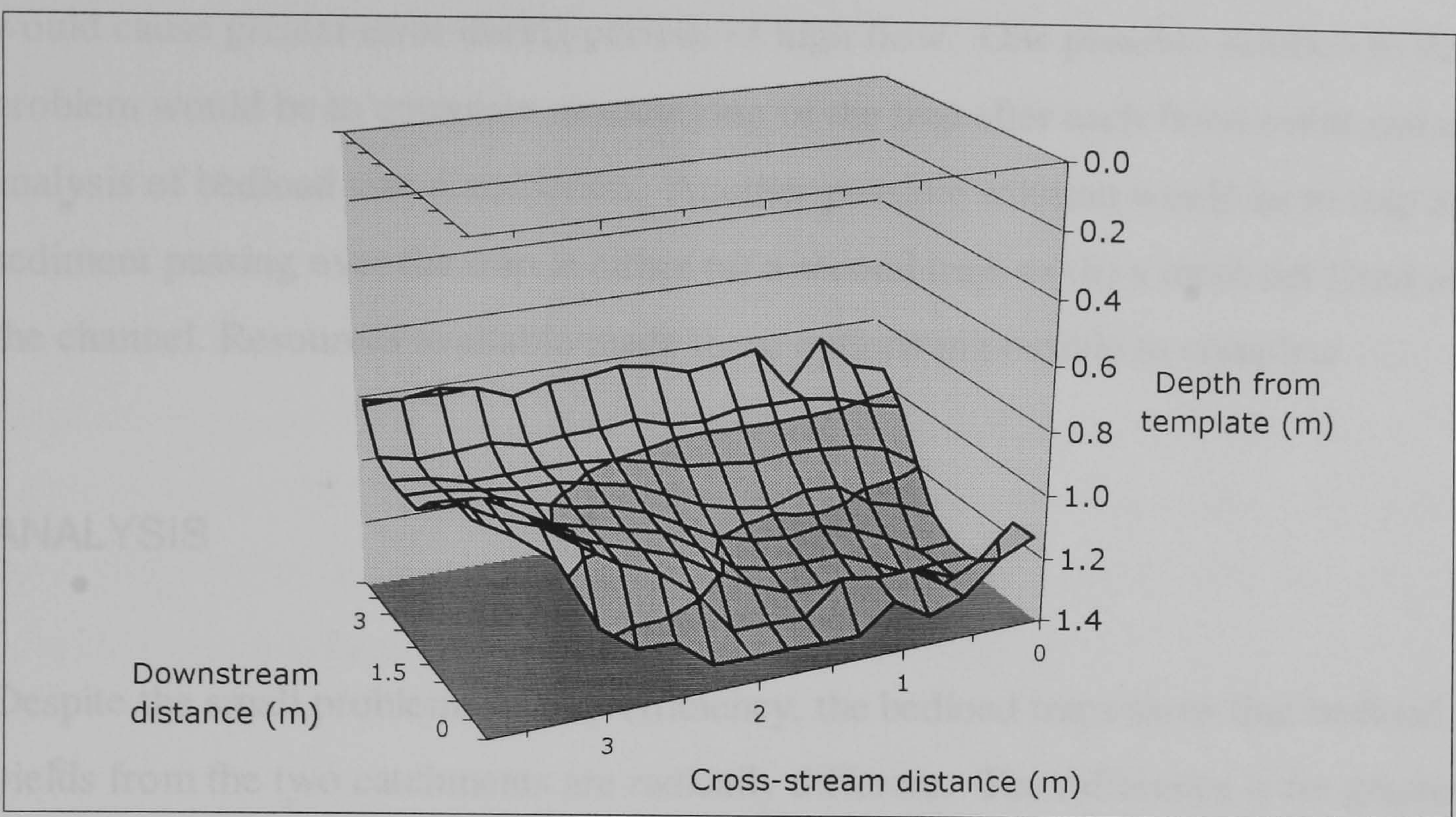


Figure 5.2. Sediment surface of Afon Cyff bedload trap 14th March 1997

Bedload material is brought in from the left-hand side of the trap where a large sediment store exists above the trap. Sediment is brought in, scoured from the back right and redistributed towards the front of the exit lip. It is envisaged that before the dip on 14th March 1997, there was scour of the trap resulting in transport of sediment through the bedload trap without this transport being recorded. It is difficult to estimate how much sediment may have passed though the trap, though it is believed to be small since little sediment was seen below the structure. Construction of future traps should, however, consider the issue of the structure influencing flow structure dynamics. Traps should be sited at a position not directly affecting the flow dynamics above the structure and not at a site of changing channel gradient or direction.

This issue means that the bedload trap in the Afon Cyff catchment is likely on occasion to be slightly underestimating the bedload yield of the channel. Because the trap had not been emptied for a significant time before the project outset and the pattern of deposition in the traps was not visible, it was not possible to pre-forecast the problem of scour. However, the extent of the difference became clear during the experiment.

There is also a temporal issue to trap efficiency, particularly during high flows; it is possible that a greater amount of bedload (particularly in the smaller size ranges) would be transported through the traps by other suspension or bouncing mechanisms. This would cause greater error during periods of high flow. One possible solution to this problem would be to complete an emptying of the trap after each flood event and a full analysis of bedload size distribution. Another possible solution would be to trap any sediment passing over the trap in either (a) a second trap, or (b) a mesh net fixed across the channel. Resources available made these options impossible to complete.

ANALYSIS

Despite the small problems of trap efficiency, the bedload traps show that bedload yields from the two catchments are radically different. The difference is far greater than that which might be associated with measurement error or differences of trap efficiency. The Nant Tanllwyth has bedload yields (t yr^{-1} km^2) eight times higher than those of the Afon Cyff and yields in the Nant Tanllwyth are well predicted by flood magnitude. In the Afon Cyff a less clear relationship with flood magnitude is seen. The figures relate to the bedload yields for the 23-month period prior to 6th June 1997.

Table 5.1. bedload yields in the Nant Tanllwyth and Afon Cyff.

	Bedload yields t km^2 yr^{-1}
Nant Tanllwyth	7.47
Afon Cyff	0.91
Factor	**8.2**

The large volume of sediment available over the length of the Nant Tanllwyth (only very short sections of the channel show any degree of exposed bedrock) suggests that the stream demonstrates features of a transport-limited system. Bedload is freely available for transport over the channel length and for the duration of the study no major changes were observed in sediment stores in the Nant Tanllwyth. If sediment were to move in small shoals in the Nant Tanllwyth (Nicholas *et al.*, 1995), these are not detectable using the techniques applied. In the Afon Cyff greater variation exists within the relationship between stream power and coarse sediment transport. This suggests that coarse sediment flux in the Afon Cyff, as well as being of a lower total volume, is limited not by transport capability but by the sediment supply of the channel itself. Large areas of the channel consist of bare, flat and smooth bedrock. In this case the likelihood of bedload coming to rest in these areas is limited as protrusion into the flow means that shear stress on free clasts is at a maximum (Brayshaw *et al.*, 1983). The propagation and existence of sediment slugs allows cohesive sections of clasts to move and deposit together. Trimble (1981) suggests that sediment slugs can be treated at a range of scales and that they may take the form of a catchment wide disturbance (which might include a change to forest land use, or a change in forest land use). However, in the context of the two-year time-scale examined in the Afon Cyff, these slugs can be considered as small sedimentary bedforms at the reach scale.

Comparison with historical records

Previous work in both Nant Tanllwyth and Afon Cyff had relied upon estimating mass of sediments trapped by emptying the trap on each visit (see section 3.4). This yielded results matching those obtained by dipping. On refurbishment of the bedload trap network, a thorough comparison of the two methods was undertaken. This analysis confirms that although the gravimetric method of recording bedload deposition did not allow frequent interpretation without actually emptying the traps, results of total bedload output can be trusted and are accurate. It is therefore possible to compare previous sediment loads taken during a different stage of the forest rotation with those taken during the time of the current project. The record of trapped sediment in the 1970s is shown in Table 5.2. Historical data are specifically given in total outputs and not yields; data from this study are presented as a yearly average, with yields in parentheses. A broken sediment record was also available from differing sources, but has not been included to avoid error.

Table 5.2. Historical records of the Nant Tanllwyth and Afon Cyff bedload traps

	Nant Tanllwyth t	Afon Cyff t	Factor
1973	69.0	51.4	1.3
1974	22.4	34.2	0.7
1975	19.9	19.5	1.0
1976	10.4	9.6	1.1
1977	75.6	14.8	5.1
1978	18.8	11.4	1.6
1979	62.9	20.8	3.0
1980	15.0	7.2	2.1
1970's average	**36.75** (41.29)	**21.01** (6.71)	**1.7**
Current research	**6.65** (7.47)	**2.85** (0.91)	**2.3**

Data from 7th July 1995 to 2nd June 1997, derived from Leeks pers comm and are total volumes of trapped sediment each year.

Yields are shown in parentheses.

The data presented from this study in Table 5.2 for both the Nant Tanllwyth and Afon Cyff are taken from analysed results for nearly two years of the same start-finish dates. The channels are therefore compared from the same periods of the meteorological cycle. The table above compares the 23 months (excluding the period from 3rd Feb 1995 to 7th July 1995, where a measurement was made exclusively in the Nant Tanllwyth) for which parallel trap data is available.

What is being examined in this section is the temporal change of the differences between forested and unforested catchments. There is a unique opportunity to return to sites reliably studied in the 1960s and 1970s and re-examine them using known techniques. The Nant Tanllwyth's measured sediment yield (accounting for catchment area) by trapping is some eight times greater than that of the Afon Cyff. Ignoring catchment area, the total volume of sediment through the bedload traps in the Nant Tanllwyth is just over twice the mass as the Afon Cyff (6.65 t and 2.85 t respectively).

There has clearly been a major change in the bedload outputs of the catchments since the 1970s. Bedload yields in the catchments presented in Moore and Newson (1986) showed yields of 38.4 t km^2 yr^{-1} and 6.4 t km^2 yr^{-1} in the Tanllwyth and Cyff respectively. This represents a difference in the two catchments' yields of a factor of 6. The difference in the yields of the Nant Tanllwyth and Afon Cyff catchments in the present study is approximately 8 so both catchments have experienced similarly decreased yields. Total yields have however decreased enormously in both catchments. In the Nant Tanllwyth, Moore and Newson (1986) record a yield of 38.4 t yr^{-1}, whereas the present study records a decrease in yield to 7.47 t km^2 yr^{-1}. In the Afon Cyff, the 1970's average is 6.4 t km^2 yr^{-1} whereas this study records 0.91 t km^2 yr^{-1}. The historical flow charts in Figure 4.7 and historical bedload yields in Table 5.2 show that the 1977 flood had a major influence on bedload yields with 75.6 tonnes measured in that year alone. The flow peak of 5.46 m^3s^{-1} was unprecedented in the Nant Tanllwyth and this has influenced the difference between the contemporary and historical readings. However, yields were not merely greater in 1977 but in all years available from historical data.

By examining data in Leeks (1992) it might be expected that bedload yield in the Nant Tanllwyth would decrease over time. In this paper, Figure 33.8 (Figure 2.1 in this thesis) predicts a peak in bedload yields after site preparation and a gradual (though perhaps not this marked) decrease in yields over time. Although the decrease in bedload yields is dramatic and without typical precedent in the literature, there are valid geomorphological reasons to explain the observations. The sedimentation of drainage ditches and the removal of coarse sediment previously liberated by ditching and planting mechanisms, should all have been completed in the relatively stable periods of forest land use of the last 20 years. In addition, the disturbances previously associated with timber harvesting seem now to have been nearly completely removed, particularly with reference to the careful felling procedure around river channels (Forest Commission, 1993). Expectations of damage to channel banks by workers and machinery simply did not materialise. In practice, either harvesting adjacent to channel banks was undertaken by hand or by using a timber-harvester which did not have its tracks near the channel banks. Consequently, none of the banks in the Nant Tanllwyth suffered any damage directly because of felling trees. Stott and Marks (1998) describe slightly increased erosion rates after the period, but this can be attributed to changes in temperature and exposure to frosts rather than to direct physical change.

More challenging is explaining the change in the bedload outputs of the Afon Cyff. The Afon Cyff is reported to have remained essentially undisturbed during the latter part of the century, but has shown a sevenfold decrease in bedload yield since the 1970s.

Analysis of the data from the 1970s (see Table 5.3) and further study of individual floods during the decade (Newson, 1975) reveals that several major floods did occur during the period. During 1977 in the Nant Tanllwyth and during 1973 in both catchments large floods were reported. However, the flood of 1973 in the Wye, reported in Newson (1975) that peaked at 65 m^3s^{-1}, did not seem to have its main source area in the Afon Cyff where maximum discharge that year was only 5.57 m^3s^{-1}. Further analysis of the period studied by Moore and Newson (1986) reveals that although stream flows were slightly higher during the 1970s, the differences in flood magnitudes were not significant (see Table 5.3). We must therefore attribute this as a real change in the sediment regime of the channel and not a change due to changes in stream hydrology of the two periods.

Table 5.3. Hydrologic variables over the 23-month bedload study period and the Institute of Hydrology's 1970s data

	Average Mean flow m^3s^{-1}		Average Maximum m^3s^{-1}	
	1970s	Present study	1970s	Present study
Afon Cyff	0.21	0.15	5.56	5.35
Nant Tanllwyth	0.06	0.05	2.31	2.25

After historical examination of the Afon Cyff catchment (Hill, pers comm) it was discovered that in the late 1960s, the failure of a mining dam (estimated to be in excess of 100 years old) occurred. This feature (Plate 5.1) is situated in the main channel of the upper Afon Cyff approximately 1.5 km above the bedload trap (1 km above the top of the experimental catchment). It is thought that the break up of this feature resulted in the release of a large volume of sediment at the end of the 1960s (Hill, pers comm). This sediment, originally built up by the dam reservoir may have continued to be in transit through the system during the 1970s. Gilbert (1917) noted the passage of sediment in the Sierra Nevada moved in wave like forms. This would explain the relatively large sediment yields in the Afon Cyff during the previous Moore and Newson study period. Field observations during summer 1999 show the possible effects of the dam breach on the results. It was clear that the construction and subsequent destruction of the dam had been a major influence on the fluvial system. Immediately below the former dam headwall (Plate 5.2) a large volume of boulder sized sediment was present in the channel. Interestingly, this headwall is the only point on either channel where a significant source of unconsolidated bedload is available for transport in the channel (Plate 5.1 and 5.2). The sediment distribution changes downstream with a rapid reduction in the size of dominant coarse material towards the upper boundary of the experimental catchment, approximately 1 km from the dam. At this point, the size distribution of the bed material becomes evenly characterised, as described in the Plynlimon section 1.5 of the introduction. What is most noticeable about the sediment distribution at present in the Afon Cyff is a sediment 'gradient' that appears to be so clearly controlled by the existence of the dam. Above the dam site, the sediment is much finer and more akin to the distribution in the experimental channel. There is then a 'step' in the grain size distribution, including abnormally large boulders in the area of the dam. Presumably these boulders were used in the construction of the dam; although there is evidence that some of the clasts were transported downstream and deposited in the pool made by the dam.

Possible effects of an old dam in the Afon Cyff catchment

A possible scenario to explain the changes in the Afon Cyff bedload trap data can be related to the dam breach as follows. During the period when the dam remained unbroken (approximately 100 years), sediment from all flood magnitudes built up in the reservoir behind the dam. All sizes of bedload would be represented and the size of the dam would make overtopping and transport of coarse sediment through the system unlikely. The material in the reservoir would therefore consist of the coarsest elements of the bedload distribution, which would not be subject to further abrasion or degradation as in normal transport circumstances. Examination of the remains of the dam suggests that construction used the largest clasts available in the catchment area with their lithology indicating that they were selected from the bedload in the channel. This 100-year period would allow a significant volume of sediment to build up, if the bedload output from the Afon Cyff was conservatively estimated at 1 - 2 t yr^{-1}, then in a 100 year period up to 200 t of coarse sediment could have built up behind the dam. This is in addition to the material used in the construction of the dam. Estimating the exact mass is difficult both intensive periods of monitoring (this study, Moore and Newson (1986)) would have both been influenced by the existence of the dam.

Plate 5.1. Upper wall of old dam site

The circumstances of the breakage of the dam are unclear as no historical records of the event exist. It is known, however, that during the 1960s, either a catastrophic failure, or the final stages of break-up of the dam took place. This would have released a large volume of sediment available for transport into the lower channel of the Afon Cyff and completely altering the bedload supply characteristics of the channel (Nicholas *et al.*, 1995). The bedrock nature of much of the channel below the dam would have allowed rapid transit of this sediment pulse though the system and would have resulted in high bedload yields during the following years. With the period immediately following the dam burst not experiencing any abnormal flows in the Afon Cyff, the largest of the material available would not have been transported, or would only have been moved short distances downstream. Section 4.1 shows how transport of the largest clasts in the Afon Cyff is size selective. Ashworth and Ferguson (1989) have suggested that equal mobility is only approached at the highest flows. This is backed up by field observations of a large number of boulders immediately below the dam site (Plate 5.3).

Smaller bedload seems to have been winnowed from the gaps between these boulders (Wathen, 1993), and transported downstream.

Plate 5.2. Site of failed 19th Century Dam

Plate 5.3. Coarse bedload a short distance below the dam site

Once this available bedload was transported, two scenarios are possible within the Afon Cyff. The channel could return to its original bedload output state, with the supply of sediment unaffected by the whole dam structure. This would only be attained if the total bedload built up behind the dam had been transported through the system. This is unlikely for two reasons; firstly, average step lengths observed by tracers suggest that bedload does not move through the Afon Cyff that quickly. Secondly, field observations show that a sediment gradient exists directly below the dam and that uncharacteristically large sized boulders exist below the site (Plate 5.3). It is possible that the old dam site still affects the sediment outputs of the channel. Sediment may be available for transport that is presently protected by the armour of the boulders, which remains in the old reservoir area and immediately below the dam site. This sediment could be liberated, and subsequently transported during a high return period flood. The coarse sediment remaining around the dam site may also affect the sediment dynamics of particles in transit from upstream. Sediment moving downstream could become trapped between larger particles, whereas previously these clasts would have been transported through the system. Observations around the dam site indicate sediment is available for transport and that in case of competent flows, this material would be transported to the lower reaches, which have large areas of exposed bedrock channel.

Alternative explanations

Other possible factors which might explain this bedload transport difference may be a difference in the monitoring technique used in the two studies. This is seen as unlikely as the same traps were used and the traps were not allowed to over-top during the study periods. Careful calibration of the spike and dip methods were undertaken on excavation and revealed no differences in the techniques.

A further hypothesis is that the Afon Cyff is susceptible to sediment slugs (Bunte, 1992; Nicholas *et al.*, 1995) or pulses not only on a small feature scale, but also on a larger temporal and physical scale (Trimble, 1981). Hoey (1992) notes that the most successful way of modelling these waves is using a three-dimensional approach, but evidence during this study is circumstantial, as resources were not available for a continuous monitoring strategy along the two channels. The model of a macro-scale pulse does however, fit well into the observations within the channel. Both results from Moore and Newson (1986) and those from this study show a relationship between discharge thresholds and bedload yield. Both studies (Moore and Newson, 1986: Table 3) show relationships in the Afon Cyff are not as strong as in the Nant Tanllwyth, though in both channels a relationship does exist. On the longer time scale between the studies, it is clear that these relationships now have different parameters, with equivalent flooding in the channels during the 1970s causing much higher bedload yields. A full analysis with all the original flow and sediment data from the 1970s would allow an assessment as to what degree that the Afon Cyff was previously a more transport-limited system, similar to how the Nant Tanllwyth is in the present day.

It is the author's view that the reason for the changes in the Nant Tanllwyth is land use change. In the Afon Cyff, the propagation and throughput of an initial sediment pulse induced by the failure of a dam structure in the late 1960s can explain the reduction of sediment output. It is unfortunate that the original intention of the study, for the Afon Cyff to act as a paired catchment, has not been entirely possible.

5.2.2. Bedload tracing: design monitoring and results

Bedload tracing methodology is given in section 3.5 with results shown in section 4.3. This discussion aims to explain the travel distance data provided in these previous sections.

DATA QUALITY ISSUES

It is thought that, for the first time, an experiment has used tracers to attempt to determine the effects of land use change on the sediment regime in a gravel bed stream. It was hoped that tracers would show detail in the dynamics of the bedload transport in the channel that would not be available from bedload trapping alone. This would also complement this total flux data.

Previous studies have shown that the nature of bedload transport is highly stochastic (Hassan *et al.*, 1984; Ergenzinger *et al.*, 1989) and that predicting travel distance based on clast size, shape and burial depth is extremely problematic. The data presented in this study support this evidence. As with the bedload trap data, it is judicious at this point of the discussion to review exactly what data were collected. The tracers seeded and monitored in the channels measured the transfer of a specified bedload size range of b-axis 8 mm to 90 mm and do not represent transport of sediment from other size ranges. This is in contrast to the monitoring of the bedload trap, which is more likely to be an inclusive measurement of sediment collected across the whole size distribution, although this depends on the trapping efficiency of the bedload traps. As the recovery rate of tracers in the smaller size categories is lower than in larger size categories, so the ability to accurately represent transport parameters of these size ranges is reduced.

In a case of 100 per cent recovery of a specific size range, it can be assumed (sample size permitting) that tracers accurately represent the movement of that size range in the channel. As soon as the recovery rate is reduced, this reliability and representation is also reduced. Tracers that are unfound due to passage through the experimental channel will force the mean travel distance presented from the remaining tracers to be under-estimated. Tracers unfound due to deep burial (and therefore effectively immobile) or lost through tracer breakage will cause the mean travel distance presented to be over-estimated. Although it is impossible to determine for what reason a tracer has become lost, it seems unlikely that the Magnotrack 100™ detector would fail to locate a significant number of tracers due to burial depth. This assumption is based on the observed high sensitivity (workable range in excess of 0.5 m) of the instrument in use and the generally shallow depth of sediment of the two channels.

Recovery rates for the study compare favourably with previous work using natural clasts in coarse gravel bed rivers. Table 4.13 shows that recovery rates in the early experimental stages are 100 per cent in the Nant Tanllwyth and approaching 100 per cent in the Afon Cyff. As the project continued, with longer residence times and with the introduction of smaller clasts, recovery rates are shown to reduce through each trace. Schmidt and Ergenzinger (1992) showed recovery rates of iron tagged tracers in the Lainbach, Bavaria, which started at 92% after one flood and reduced to 17 % after 4 to 8 flood peaks. Other studies show recovery rates varying from 8% using painted clasts (Takayama, 1965) to between 90 and 93% using magnetic clasts (Hassan *et al.*, 1991). These high recovery rates by Hassan *et al.* (1991) were notably in ephemeral streams where reliable low flows and a clement tracing climate made for ideal conditions for relocation. In the light of this previous literature, it is suggested that recovery rates within the two Plynlimon channels are high enough to present useful data.

Measuring travel distances and velocities (if any time function is included) can be based on a real or virtual approach. Ergenzinger *et al.* (1989) and Hassan *et al.* (1992) also highlight this. Essentially the analysis by which this project has been undertaken is a combination of these two, as it combines an element of virtual travel in discharge over a threshold as well as total distance travelled. With the field equipment available, and the number of traces made over a 2-year period, it is impossible to measure exactly the real velocity of tracers in transit.

ANALYSIS

Introduction

The aim of using tracers was to establish differences in the bedload transport regime of the two channels and to investigate how felling of a portion of the Nant Tanllwyth would affect that bedload transport regime. It would be desirable to model exactly the bedload transfer process in both channels and examine the differences between the channels in this manner. The data presented in tracing section 4.3 shows that the variability of the results makes this impossible and indeed the project does not set out to achieve this. Ferguson *et al.* (1991) highlighted the difficulty of disentangling suspended sediment data in the Loch Ard catchments following forest operations. Fluctuations in flow regimes of paired catchments and natural variability in suspended sediment concentrations made conclusive evidence of changes due to forest operations difficult to disentangle. The large number of variables influencing bedload transport (Brayshaw *et al.,* 1983) were not, and cannot, be measured fully in an experiment involving this number of tracers.

The approach used in this study was to attempt to find 'patterns' within the geomorphological data monitored. Regression analysis of clast travel distance was carried out using field predictors of water depth, burial depth, channel position and discharge thresholds, as well as tracer parameters of size and shape. No relationships were found between travel distance and the controlling parameters of burial and water depths, nor was starting channel position found to a control the subsequent travel distance of a clast. In certain circumstances however, these factors have been proven to control the probability and distance of sediment transfer in a gravel bed river (Hassan, 1990).

Tracer clast travel distances in other rivers throughout the world have varied according to the study location. Although mean annual travel distances are not reported by Ergenzinger *et al.* (1989), the study shows 80% of clast moved between 200 and 500 m in a single flood event (discharge peaking at 18 m^3s^{-1}). On the same Lainbach reach, Schmidt and Ergenzinger (1992) report mean travel distances of clasts of mass 330 g to 5020 g at between 15 m and 33 m per flood. In this study, return periods of these floods are not determined and thus the magnitude of sediment transport in the rivers is not estimated. Ferguson and Wathen (1998) working in the Allt Dubhaig, Scotland, measured mean travel distances per year in six reaches. Results varied between 22 m yr^{-1} and 95 m^{-1}, the highest travel distances associated with the steeper upstream sections of the channel. Although the Dubhaig has significantly higher discharge (peaks exceeding 20 m^3s^{-1}) than the Nant Tanllwyth or Afon Cyff, mean travel distances of clasts in this study are as high as 48 m yr^{-1} in the Nant Tanllwyth and 27 m yr^{-1} in the Afon Cyff. There is variation between the two channels, but it is in direct contrast to the hydrological character of the channels, with the Afon Cyff having peaks some three times higher than the Nant Tanllwyth.

Travel distances of tracers and clast size

Figure 4.26 shows that in the Nant Tanllwyth, a good relationship between flood magnitude over 0.3 m^3s^{-1} and mean travel distance of each trace exists, with an $r^2 = 0.93$ ($n=10$, $p<0.001$). This is for the study period inclusive of pre- and post-felling phases. It is therefore possible to make estimations on the likely effect of floods within the limits of flood intensities studied on future bedload travel distances. Further analysis however, makes it clear that prediction of the travel distance of any one clast is not possible. It is not possible to compare this value with the Afon Cyff, as the small value of *n* makes it impossible. As with the study of data from the bedload trap, bedload transport in the Afon Cyff is less predictable than in the Nant Tanllwyth. It is simply not possible to make predictions for mean travel distances of clasts based on any measure of flood magnitude.

Relationships between travel distance and a number of discharge parameters were attempted. The most successful approach proved to be calculating a mean distance of movement for each trace and comparing this with flood magnitudes (Figures 4.25 and 4.26) or representing the results as falling within an 'envelope' of values (Figures 4.27 to 4.30). This confirms observations shown in Figure 6 of Schmidt and Ergenzinger

(1992) where an envelope of values exists but no functional relationship between predicting parameter and travel distance is forthcoming. Individual tracers show a large variation in clast travel distance in relation to mass and b-axis (Figures 4.27 and 4.30). When these tracers are sectioned into size categories (Figures 4.31 and 4.32) size selectivity emerges and this selectivity favours smaller over larger clasts. This is particularly clear in the Nant Tanllwyth. With the analysis of tracer pebbles showing tracers in the small size ranges moving further, combined with their reduced likelihood of relocation (also forcing the figure to be artificially low), this observed size selectivity can be considered real.

Hassan *et al.* (1992) also analyses the relationship between travel distance of each size range and discharge parameters and found that no size range exhibited a stronger relationship than any other. The confirmation of these findings in the present study may be partially explained by the limited size range studied, with tracer clasts not fully representing the small size ranges. More likely, however, is that the findings represent the stochastic nature of the real transport regime of each size fraction, as illustrated by the general scatter in the results and that all of size ranges are equally difficult to model predictively.

The travel distance data from the Nant Tanllwyth and Afon Cyff has shown that the Nant Tanllwyth is more predictable in terms of mean travel distances per flood (see Figure 4.26).

Figure 4.31 shows that this predictability extends to the size selectivity of the Nant Tanllwyth, tracers within the 8 -11 mm category moving on average more than six times as far as tracers in the 90 - 128 mm category. The rate of transport changes smoothly through the size distribution. In the Afon Cyff, however, this trend is not as pronounced with the smallest size range contradicting the pattern. Unfortunately, the reduced number of traces in the Afon Cyff means that it is difficult to use mean travel distances to develop a good relationship, though by visual examination, there is huge variation in the travel distances at lower flood indices which is not readily seen in the Nant Tanllwyth (Figure 4.26).

An explanation of why travel distance is more selective in the Nant Tanllwyth than in the Afon Cyff is required. There are several possibilities that are discussed below.

1. Different particle interlocking structures between the two channels;
2. deeper water present in the Afon Cyff (table 1.3), and
3. large scale sediment storage structures within Afon Cyff.

The evidence from both bedload traps (section 5.2.1) and tracer experiments shows that transport in the Afon Cyff is both supply-limited and occurs in shoals: sediment exists on the channel bed but it is not being readily entrained. Billi (1986) observed the higher number of pebble clusters in the Afon Cyff than in the Nant Tanllwyth, with 888 clusters and 236 clusters respectively. These clusters would partly explain the reduced selectivity as initiation of transport relies first on the break-down of the clusters, after which point transport can occur throughout the range. Examination of individual sediment structures did not take place during the period of fieldwork and it is therefore not possible to confirm if these observations from Billi continued during the study period. However, with no relationship with burial depth, both channels exhibit a pattern of 'moving mat' transport, where the active layer is mobilised during flood events. If the entire active layer does become equally mobile at the time of excess threshold, but there is still evidence of size selectivity of transport distance, then it is not the entrainment threshold that is crucial but instead the ability of the flow to continue transporting the clast during the flood event. It would be interesting to have been able to trace after every flow event thought to exceed the entrainment threshold and particularly to be able to trace clasts from a natural starting position. This might have revealed clasts being entrained only from the bed surface: at one point the bed must pass through this stage, as observations suggest that the formation of a true armour layer does not occur in these channels.

The shape of the Afon Cyff channel results in a deeper thalweg than in the Nant Tanllwyth. The increased lift coefficients occurring in shallow streams would be exaggerated in the case of the Plynlimon sediments that are made up of predominantly discs and blades. This would lead to higher thresholds of entrainment in the Afon Cyff and generally lower levels of transport.

During peak flows, bedload is definitely deposited in shoals in the Afon Cyff, which during normal high flows, simply deflect the current around them and along the thalweg (often smooth bedrock). When sediment mobilising flows do occur, the entire bed becomes entrained and these shoals move into new positions, though maintain a series of bedforms in the channel. These bedforms can form more easily partly due to the difference in size of the two channels. Newson and Harrison (1978) and the authors results show that channel widths are greater in the Afon Cyff. Observations in the Nant Tanllwyth on constrained channel banks mean that even moderate discharges can fill the channel bottom. This also explains the pulsing nature of bedload trapped in the Afon Cyff shown by a lower correlation coefficient of trapped bedload to flow thresholds. The nature of the bed of the channels themselves, as highlighted by Billi (1986) is significant in explaining the stochastic nature of the bedload transport and the wide variation around the means observed.

It is not possible to conclusively rule out any of these factors, as all have a potentially important role in why the transport regime is different in the Afon Cyff. The impact of sediment clusters is particularly difficult to quantify as no observations were made. However, observations did show that large numbers of tracers were found on lateral channel bedforms and that in many central channel areas, no sediment stores existed. This, in tandem with the depth of water in the Afon Cyff, would have had a controlling influence on sediment transport rates.

The influence of flood magnitude

When each individual flood is analysed (Figure 4.33), size selectivity is again clear in the Nant Tanllwyth but less so in the Afon Cyff (Figure 4.34). Where each flood period has been organised based on its magnitude, the trend lines (Figures 4.35 and 4.36) show that tracer movement in the Nant Tanllwyth is size selective during both large and small magnitude events. This is not as clear in the Afon Cyff, where we see crossing of the trend lines of each size fraction and from the original data, significant variation from each flood event. This is not fully expected as Figure 4.32 shows that a general pattern exists in the Afon Cyff whereby (apart from the smallest category) smaller particles are transported further. The analysis by flood size shows that, specifically during the largest flood period (trace 4), tracers in the smallest categories moved less than in larger size ranges. In the final trace (trace 5), the trend is reversed, and although there are smaller overall travel distances, size selection is clearer. What is causing these observations?

It was hypothesised that there would be a relationship between the previous flood event and the variation in transport rates of individual size ranges. The approach of analysing size ranges under different starting conditions was undertaken by Brayshaw *et al.* (1983) who examined the effect of particle clustering. However, the data that were required to model the effects of clustering were not available in this study, though it was hoped that sediment burial depth and water depth of particles would explain some changes in transport. Hassan (1990) found that buried tracers moved lower distances and tracers on the surface had a more than 80% chance of being entrained. Significantly, for both channels in this study, burial depth was found to have no relationship to the travel distance of clast, or the probability of entrainment. Both channels exhibit a "moving mat" style of transport, with burial depth having no measurable effect on travel distance.

Travel distances can be expected to vary according to bedload size, channel slope, bed roughness and flood maxima. In the case of a tracer positioned on a flat and smooth bed, a larger tracer would require a greater stress exerted on it to entrain it, and thus the probability of the tracer moving a long distance is reduced. This is particularly relevant in the predominantly bedrock Afon Cyff channel, characterised by a smooth bed and hence low bed roughness. The field results show, however, that this channel has not exhibited the high bedload output characteristic of this phenomenon. This may be because the overriding control on the sediment regime of the Afon Cyff is reduced availability of sediment. Indeed the total volume of sediment available for transport on the surface of the channel is lower than in the Nant Tanllwyth. Whether this is controlled by the existence of the dam higher in the catchment was discussed earlier.

5.2.3. Combining the data sources

One issue arising from this study is how well data from the two main monitoring sources can be combined. An essential question is: "can a relationship be established between bedload trap volumes, mean tracer travel distances and flood magnitudes?" If this is the case, then it should be possible to use a tracer experiment to estimate total yields of any stream without the need for bedload traps. This study has not made an attempt at modelling the physical mechanisms of entrainment discussed in the section 2. It has attempted to build a pattern of transport under two contrasting land uses, as well as to compare the dynamics of two separate streams. The two data sources, the bedload traps and individual clast tracing, give rise to findings that are clearly related to each other, but provide results in different formats. Table 5.4 below summarises these results.

Table 5.4. Summary of results from tracing and trapping experiments

	Bedload yields $t\ km^2\ yr^{-1}$	Bedload Total $t\ yr^{-1}$	Mean tracer travel distances $m\ yr^{-1}$
Nant Tanllwyth	7.47	6.65	39.74
Afon Cyff	0.91	2.85	27.26
Factor	**8.2**	**2.3**	**1.5**
Nant Tanllwyth post-harvest	No proven change	N/A	Proven increase

Although the two monitoring sources are both measuring the flux of bedload, they are measuring it using different methods and with different spatial parameters. The sediment yield based on measurement using bedload traps measures the exact amount of sediment (based on the assumptions in 3.2) passing a specific point in the channel (the trap at the end of the experimental reach). This measure is commonly expressed as a total volume of bedload discharge per unit area of catchment. Tracing individual clasts in the stream (and expressing this as the function mean travel distance), measures transport of a sample of a specific size range, along an experimental channel reach of specified length. The result is that the bedload flux in the two channels can be expressed in three different ways and the results in this study show factorial differences in the outputs of between 1.5 and 8.2. How can this be resolved if we accept the relationships between flow thresholds and bedload outputs that have been constructed in earlier chapters?

Bedload movement measured using tracers describes the dynamics of clasts within the channel alone and takes no account of catchment area, tracers measure the transport of the existing sediment using tagged clasts to integrate themselves as part of the sediment mix. Bedload yield measured using bedload traps can vary significantly in a temporal sense (Hoey, 1992). In the long term, trapping accounts for the inputs of coarse sediment from catchment sources such as channel banks and tributaries. It then expresses the value of sediment yield based on the size of the catchment. In the short term however, traps are more likely to measure (especially accurately in a transport-limited system) the volume of sediment that is stored in the reach immediately above the trap itself, which may be part of a sediment wave or sheet (Whiting *et al.*, 1988) on a variety of scales. In this case, to add a factor of catchment area is surely inappropriate? In addition, to expect the trap to show changes due to new sediment regimes much higher up the catchment would be unrealistic.

Perhaps the problem of matching the methods does not exist in the short term, as both systems measure the dynamics in a short reach of channel and not in the whole catchment. The tracers that were injected into the most active tributary of the Nant Tanllwyth (section 4.3.2) did not reach the main channel; with the lowest tracers in the tributary moving less than 20 m over the two year period. Wathen (1995) suggests that the only inputs (on the reach scale) to bedload transport are bank erosion and the channel itself. If travel distance of tracers averages between 25 and 40 m yr^{-1} in the two channels, one might rightly expect bedload traps to take in excess of 10 years to register the input of sediment changes occurring between 250 and 400 m above the respective bedload traps. In the Nant Tanllwyth, there is no significant tributary or eroding bank face that might be expected to contribute bedload within 80 m upstream of the bedload trap. It could be assumed then that the majority of sediment measured in the Nant Tanllwyth trap was actually within 80 m of the trap when measurement started; certainly that length of channel could accommodate the 12 t of bedload trapped. It is concluded, therefore, that it is unlikely that the bedload traps could, in the short to medium term, detect any change in bedload yield due to timber harvesting. In addition, the probable reason for the lower bedload output of the Afon Cyff is simply because there was not the sediment available to be transported, either because their was simply no supply from upstream, or that the lack of supply had in places caused patchiness in armour in sediment stores. Under these conditions of low or non existent sediment inputs, static armour has been shown to form (Sutherland, 1987) and might prevent significant transport of material that is protected under this armour. This may be occurring in the Afon Cyff preventing high bedload yields.

It is not the purpose of this section to manipulate the data so the Nant Tanllwyth and Afon Cyff bedload yields respond identically to flow thresholds, but instead to explain why the magnitudes of the different methods of monitoring bedload appear to be different in the two channels. Table 5.3 shows that the difference in magnitude of bedload yield from the channels (the Nant Tanllwyth is eight times greater than the Afon Cyff) is not comparable to the difference in magnitude of tracer travel distances (a factor of 1.5). The removal of the catchment area factor brings the two figures far closer with a difference in magnitude of 2.3. This removal is justified as it has been shown to be inappropriate to use a catchment area function at this timescale of analysis.

Tracing describes the probability of a clast of a certain size travelling a certain distance, not the same function as measuring the total coarse sediment output of the channel. The experiments monitor sediment that differs in both size distribution, as well as point of measurement. Perhaps this difference is due to the failure of tracers to represent the small size ranges? Observation of the size distribution of the bedload trap material shows that fine sediment (other than what would normally be classed as bedload) is included within the distribution. If the amount of fine sediment in the channels is different (the Nant Tanllwyth has a significantly greater suspended sediment load (Stott and Marks, 1998)), then the proportion of the trap distribution made up of this sediment is likely to be different. Sediment settles out of suspension under conditions of low bed slope angles, deep water and lower roughness elements. This describes the relatively stable environment of the bedload trap, conditions not available elsewhere in the channels. If the Nant Tanllwyth does have a higher concentration of fines in the bedload trap, this would partly explain the differences in the factors between the two channels by over estimating the yields of true bedload in the Nant Tanllwyth.

THE IMPACTS OF TIMBER HARVESTING

There is conclusive evidence to show that travel distance of tracers increased post-harvesting. The change in tracer travel distances has been demonstrated as a real change based on the discharge over the 0.3 m^3s^{-1} threshold (Table 4.13). In contrast, the total discharge of bedload from the channels using bedload trapping has not been proved to change. Although total bedload yield increased slightly, when analysed against the hydrology of the two phases, only a 5 % increase was observed (against the 0.3 m^3s^{-1} threshold). Either this observation is due to the monitoring procedure or there is a genuine physical explanation for the results. The possible reasons for tracer and trap data not displaying the same trends have been discussed above.

Stott and Marks (1998) reported an increase in suspended sediment in the Tanllwyth during the felling period. The felling period was characterised by low flows and the coarser part of this mix would not be transported during these flows. This would result in the infilling of gaps in the coarse matrix (very noticeable in the Tanllwyth bedload trap during summer months) and would likely make entrainment of coarse bedload and tracer gravels less probable. Exactly the opposite, however seems to have occurred, with tracer travel distances increasing equally in all size ranges (see Figure 5.3). The contrast between the increases in sediment from forest work seen in previous studies (Stott, 1987) with the *no change in the catchment* situation in the Nant Tanllwyth during harvesting could not have been clearer; it is unlikely that significantly more bedload entered the channel, as both bank erosion and tributary sediment source changes were limited by the nature of harvesting.

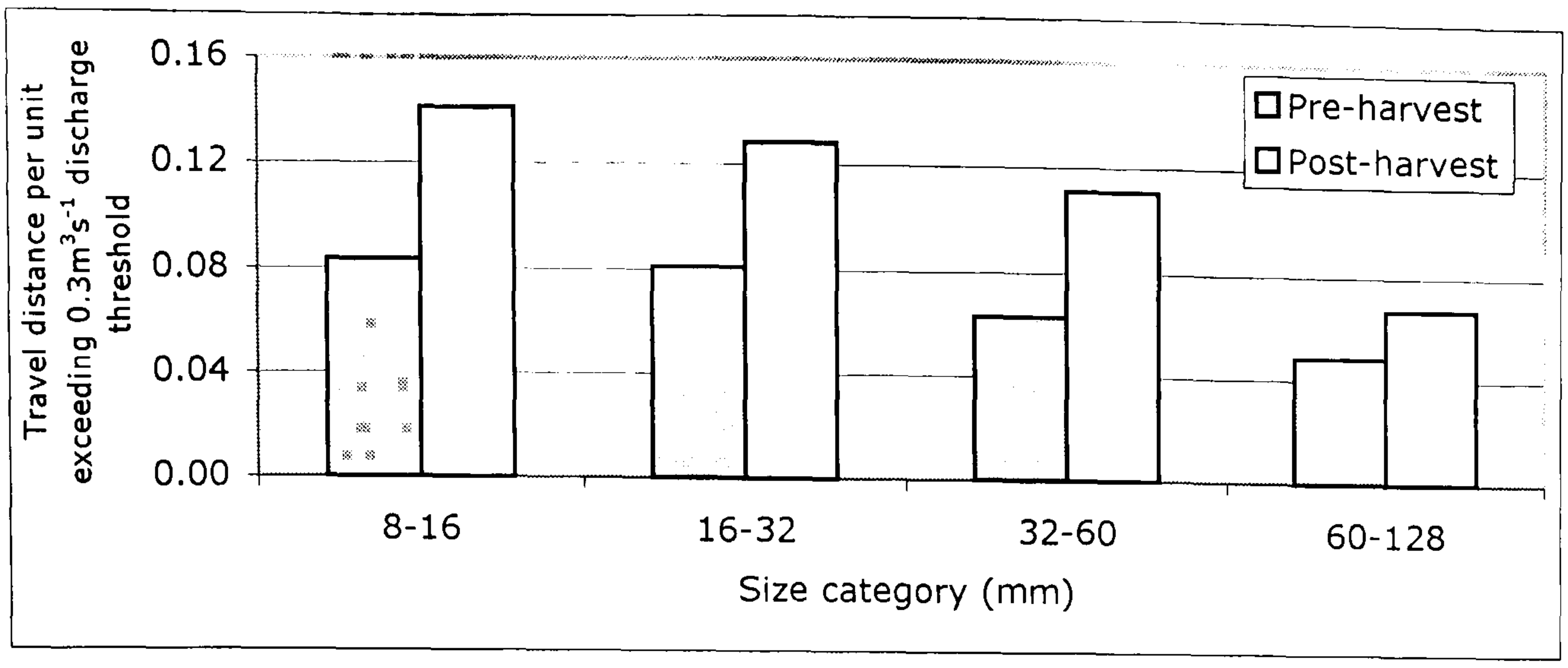


Figure 5.3. The impact of harvesting the Nant Tanllwyth on pre-harvest and post-harvest travel distances in 4 clast size classes

The observed increase in tracer travel distances in the post-harvesting period is made based on the assumptions of data made dimensionless using the flow thresholds. The period after the felling period did in fact experience the two greatest flood events (Nant Tanllwyth periods 8 and 9), this is particularly clear in Figure 4.33. With flood periods eight and nine containing the two periods of highest discharge during the study (2.25 m^3s^{-1} and 1.48 m^3s^{-1} respectively), it is likely that the relationships between tracer travel distances at these high flows is different to lower flood peaks (say the 0.3 or 0.5 m^3s^{-1} threshold). This is partially underlined by the mean travel distances of all tracers (see Figure 4.25) which shows the period with greatest flood activity over the 0.3 and 0.5 thresholds (trace 8) to have a disproportionally greater mean travel distance to flood magnitude. It is difficult for any mechanism (further to the standardising to thresholds already attempted) that can determine and disentangle the effects of land use change.

5.3. Abrasion

The results suggest that greater mean travel distances of tracer clasts may account for the difference in weight loss between tracers in the forested Tanllwyth and the grassland Cyff channels. There is no doubt that bed sediment is much more mobile in the Tanllwyth channel with travel distances being higher than those in the Cyff and it is likely that drainage ditches excavated in the 1930s at the time the plantation forest was established continue to supply some sediment to the main channel. The lower mean travel rates reported in this study for the Cyff concur with these findings.

In terms of shape of clasts, rods and spheres have the highest mean travel distances, but while rods have highest mean weight losses, spheres have the lowest. This may be accounted for by the fact that their shapes make them more suited to rolling and, once in motion they are less likely to be deposited due to imbrication and bed armouring. Spheres are least likely to break while in transport and, predictably, their mean weight loss is the lowest of the four shape classes. Spheres, however, are very uncommon in these channels and the extremely small sample size renders these inferences at best suggestive, and at worst unreliable. Rods, in contrast, seem to be more prone to breakage. Indeed, the maximum weight loss for all tracers was 57.2 % and this clast was a rod. The next highest weight loss for rods is 13.0 % which implies that breakage of clasts is relatively unusual and that corner rounding and edge chipping are more likely to account for the weight losses observed. However, one limitation of the approach taken is the inability to document and quantify the different weight loss mechanisms that may be operating. These mechanisms may include abrasion of clasts against bedrock and other sediment in movement, sandblasting by the sand component of the suspended or saltating load, edge/corner chipping or even splitting as illustrated above. In the light of these data, it is not possible to determine whether abrasion processes operating in each channel are different, or operate in different ways. Further work based on the techniques used by Brewer *et al.* (1992) will be required to answer these questions.

Regression and multiple regression have been partially successful in explaining percentage weight losses in terms of travel distance, particle shape (Krumbein's Sphericity Index) and relative clast size (D_i/D_{50}). Multiple regression was able to explain 42.5 and 30.6 % of the variation in tracer % weight loss in the Afon Cyff and Nant Tanllwyth respectively. This suggests that other factors such as the precise geological composition of the clasts are almost certainly important in predicting abrasion rates. In regression analysis the least useful predictor was sphericity which was not statistically significant in either channel, whereas travel distance and relative size (D_i/D_{50}) were both statistically significant ($p < 0.01$ in the Afon Cyff; $p < 0.025$ in the Nant Tanllwyth).

The findings of this study suggest that weight losses of natural tracers is likely to be more dependent on clast size and travel distance, with clast shape being of secondary importance. This contrasts with the "abrasion in place" processes (bed load over-passing and sandblasting) monitored in the Tanllwyth channel by Brewer *et al.* (1992) and the "vibratory" processes proposed by Schumm and Stevens (1973).

These findings may help to explain observed trends in downstream fining and bed sediment character of alluvial channels and the production of fines from in-channel abrasion processes. They add significantly to a relatively small dataset from which natural in-channel abrasion rates may be assessed. Consideration should be given to including them as a component in models that attempt to predict downstream changes in shape and size as well as the production of fines from abrasion processes.

Section 6: Conclusions

The conclusions section aims to draw together the thesis by summarising the main findings, considering what implications these findings have on the future management of British upland forests and suggesting directions for further or more intensive study.

6.1. Summary of findings

The research in this thesis aimed to determine how, or if, bedload flux in the channel of the Nant Tanllwyth would be affected by the harvesting of 20 % of the catchment area's plantation tree cover. The project aimed to determine total bedload yield of the Nant Tanllwyth and Afon Cyff, as well as establish patterns and relationships in the transport of bedload within the two channels. These aims were achieved using bedload trapping and tracing in the channels over a period that included the harvesting of the Nant Tanllwyth. The study has given rise to the following conclusions.

- By a visual examination of timber-harvesting operations during Spring 1996, the impact of direct forest operations on the liberation of coarse sediment by disturbance of catchment slopes was minimal. Ground damage was limited by the use of brash matting and new forest-clearance machinery meant little disturbance to either stream channels or catchment slopes. Notably, coarse woody debris jams were entirely absent from the main channel of the Nant Tanllwyth. Evidence has since emerged to suggest that debris accumulations have occurred in tributaries of the main channel, in addition there are opportunities for developing vegetation to colonise previously light starved areas when under forest canopy. These factors might be limiting coarse sediment supply to the Nant Tanllwyth.

- In the Nant Tanllwyth, using bedload traps to monitor bedload outputs was generally successful, as a clear linear relationship was constructed between excess flow over discharge thresholds and total bedload outputs. The relationship constructed allowed an examination between the pre- and post harvesting phases and bedload outputs were proven not to change significantly after harvesting. Although the relationship between bedload outputs and stream discharge remained stable, yields from the Nant Tanllwyth, both pre- and post-harvesting, were significantly higher than from the Afon Cyff when expressed as total outputs, or yields inclusive of catchment area.

- Yields in both catchments have been shown to drop dramatically since the 1970s when sediment yields from the Plynlimon catchments were first reported. Notably, both Nant Tanllwyth and the Afon Cyff have experienced dramatic decreases in bedload yield. This is attributed to an historic dam structure and stabilisation of sediment sources under forestry in the Afon Cyff and Nant Tanllwyth respectively. It is concluded that using the Afon Cyff as part of a future paired catchment study must fully account for the presence of the dam changing the natural sediment regime of the channel.

- Using tracers to examine bedload flux in both streams underlined the stochastic nature of the travel distances of individual clasts. Good recovery rates were obtained due to the size of the channel and techniques used for tracing. Preferential transport of smaller clasts did occur in both channels, particularly clearly in the Nant Tanllwyth. The influence of clast burial, shape and sphericity in the channels was secondary.

- In the Nant Tanllwyth, tracer data showed that after the felling period, travel distances of clasts increased. This is thought to be independent of any change in hydrology as travel distances were made dimensionless using a flow threshold index. This increase is particularly difficult to explain but can be partially attributed to the stochastic nature of bedload transport in upland reaches and hydrographic variables not determined by the type of analysis made.

- Weight losses of natural tracers is likely to be more dependent on clast size and travel distance, with clast shape being of secondary importance. It is not anticipated that the amount of abrasion in the channels affects the overall bedload yields of the channels and hence this is unlikely to be an important management consideration.

Harvesting using ecological harvesting techniques has reduced the short-to-medium term effects on coarse outputs of timber commercial harvesting, The implications for forest contractors are discussed below.

6.2. Management implications

In Spring 1996 the partial felling of the Nant Tanllwyth catchment was expected to bring widespread change in the character of both the channel and its bedload outputs and transport. Evidence from previous studies worldwide had shown the likelihood of loose brashings forming debris jams resulting in severe bank erosion. The proximity of forest workers and heavy machinery has also been shown to cause erosion. These changes might have manifested themselves on the sediment regime of the Nant Tanllwyth as instant and dramatic increases or decreases in total yields. In addition, if significant new sediment input had occurred from banks or ditches, the volume of incoming sediment might simply have buried tracers *in situ* and made them unavailable for further transport.

In practice the harvesting of the 20 per cent of the Nant Tanllwyth, even though it was directly adjacent to the study reach, did not have a dramatic effect on the sediment flux and yield of the channel in the short term. Bedload yields remained stable, most notably responding similarly to the flood peaks coming in the post-harvest phase as to those peaks pre-harvesting. Bedload tracer movements were increased (but notably not in any specific size range) and due to the difficulties in disentangling increased peak flows in the post-harvesting period, the validity of these data are difficult to quantify.

The possible formation of coarse woody debris jams was monitored in the channel and catchment during and after harvesting. Although most studies concentrate mainly on the removal of naturally occurring debris jams in non-plantation catchments, some work for example (Bryant, 1980; Leeks, 1992) has shown how harvesting can promote these features with brashings and excess logs. Smith *et al.* (1993) showed that after development and experimental removal of debris jams, sediment transport increased along with increased transport energy and bank erosion. The effect was that the stability of the sediment regime was affected in the medium term with continuous adjustments made to bedforms in the channel. None of these major dams were to be found in the Nant Tanllwyth, indeed during the study period, only on one occasion was a log found anywhere in the channel. Keller and Swanson (1979) observed a decrease in bank stability as flow is deflected against channel banks and greater sediment inputs due to debris jams. Keller and Swanson (1979) also note that at peak discharges floating debris itself may batter the bank sides and cause erosion. The attempts made by the forestry operators in the Nant Tanllwyth to ensure that the channel banks were undisturbed proved to be successful, with little or no effect on either the channel or the banks themselves.

Plate 6.0. One machine Harvester processing felled tree, Nant Tanllwyth.

There is little doubt that the care taken by forest workers, the felling techniques employed and the harvesting machinery (Plate 6.0) used had an enormous influence on the low impacts of the partial felling on the Nant Tanllwyth catchment. However, examination of figure 4.1, where the dashed vertical line shows the felling date, highlights the significant period of low flows and rainfall during and immediately following the felling period. The methods used in this case would still have caused increased erosion under wet conditions where surface soils are more susceptible to erosion from machinery and overland flow sources. These methods differed from the work undertaken in the Balquhidder catchments where aerial skylines, drags and forwarders were used, potentially more erosive methods.

A summary of harvesting guidelines is given in the Forests & Water Guidelines (Forestry Commission, 1993) and the pertinent practical considerations of these are given in Table 6.1.

Table 6.1. Summary of working checklist for harvesting operations (Forestry Commission, 1993)

- Consider phased felling or reducing the scale of operations.
- Fell and extract in sensitive areas during dry weather.
- Protect underground culverts and pipelines.
- Avoid skidding on soft soils.
- Choose dry sites for stacking timber well away from watercourses; do not block roadside drains.
- Plan extraction to minimise stream crossings.
- Use pipes or a log bridge where extraction routes must cross watercourses.
- Avoid long ground extraction routes on steep ground, especially in high rainfall areas.
- Do not let machines work in streams.
- Fell trees away from streams.
- Keep branches and tops out of streams
- Use brash mats wherever necessary to protect the soil.

These guidelines were well adhered to in the felling of the Nant Tanllwyth for both timber harvesting and extraction. It seems that the acknowledgement of the importance of small first-order streams on the sediment regimes of larger rivers, is manifested in practical operations.

This section aims to suggest further improvement to these guideline. Forest operators now harvest the area immediately around the channel by hand and remove brashings back from the channel. This is shown in Plate 6.1 where the area in the bottom section of the photo has recently been harvested.

Plate 6.1. Clearfelling has taken place adjacent to the channel banks: nearly all brashings from the area around the channel have been removed

The importance of the timing of this work should not be underestimated. The Forest and Water guidelines should include direction on the hydrological and meteorological conditions under which work can be undertaken near watercourses. It would be impractical to expect foresters to discontinue work at the advent of a rain shower, but guidelines for working around watercourses during intense periods of rainfall, or in highly saturated conditions could be easily followed. The recommendations would only apply in close proximity to watercourses (including forest ditches), where stream and ditch banks are susceptible to damage. This recommendation could be built into the current document.

Undertaking this hand felling policy near the channel is in the interest of a forester who wishes to maintain the channel in its current state. The removal of brashings and careful felling avoids the interference with the medium to long-term sediment dynamics by continuous formation and destruction of debris jams. Specific care also needs to be taken in the removal of logs in the vicinity of the channel banks. A consequence of the partial felling of the catchment combined with the hand felling adjacent to the channel was observed approximately 200 m above the experimental section. The harvesting area was delimited using the main channel and several of its small tributaries as borders for each section. This led to a neat but exposed 'wall' of trees, which was susceptible to wind action. With the shallow root systems of the plantation (particularly around the channel where furrows did not appear to have been as deeply ploughed), the trees were unable to support themselves and became windblown. This is shown in Plate 6.2 below.

Plate 6.2. Wind blown trees on the upper Nant Tanllwyth in July 1999

The effect of this wind exposure both damaged and uprooted trees. In addition, because the interface between the harvested and standing areas was the channel, the bare roots of the trees broke up the banks of the main channel. Some of the bases of these uprooted trees were in excess of 3 m in diameter and loosened significant volumes of non-cohesive sediment that might be entrained and transported into the channel, particularly during high and over-bank flow events. The problem (which did not manifest itself immediately) could be solved by ensuring watercourses were not used to delimit the partial clearfelling areas. If for management reasons this was impossible, it would be appropriate to leave a small standing (but significant) buffer of trees on both sides of the channel so that the entire stream area was protected from wind blown trees. Alternatively, protection could be built into the harvesting programme by felling a buffer on both sides of the channel, so that the wind blow would occur far enough from the watercourse that exposed roots would not damage the channel and banks.

Undertaking techniques for minimising the impacts of harvesting, such as hand felling next to watercourses and laying down matting for heavy machinery has significantly reduced erosion to both the channel itself and the surrounding slopes. The advent of the one machine harvester, used for economic rather than environmental reasons, has in itself brought benefit to the environment of the catchment. Work is undertaken at a much faster rate than before and fewer heavy machine hours are required in the catchment. Machinery to transport the logs can move easily over the felled area of the catchment, as brashings are well ordered and sorted into matting and the tops of stumps are cut low and evenly. This means that fewer new forest roads are required, roads that have proven to be significant sediment sources in previous studies (Painter *et al.*, 1974; Ferguson and Stott, 1987).

It is important to note that selective transport of small clasts does occur in the Nant Tanllwyth; if the change in catchment land-use results in an input of small grained sediment in the medium to long term, then this fraction would be preferentially and efficiently transported. It is therefore important to ensure that sediment sources of small bedload are minimised in all future harvesting operations.

Future forest practice

The net effect of undertaking ecological harvesting has been that enormous efforts have been made to prevent damage to the small first order watercourses such as the Nant Tanllwyth. The concentration on these watercourses has possibly been to the detriment of the network of small ditches and sub-tributaries of the stream (some of which are ephemeral in their discharge) which nevertheless make a valuable contribution to peak flows and sediment inputs into the channel. Evidence for this has been shown by the subsequent examination of two such tributaries running into the Nant Tanllwyth, one on the clearfelled side and one that remains forested. This is shown in Plate 5.6.

Plate 6.3. Tree brashings and lops in a small ephemeral sub channel of the Nant Tanllwyth, October 1997.

A large volume of organic material (including branches and brashings up to 70 mm in diameter and 2 m in length have either clogged the channel, or have completely covered it over. Preliminary tracking of tracer clasts in these two streams (Stott, in prep) suggests that travel distances are in excess of 5 times higher in the sub-tributary remaining forested and that the limitations of transport in the clearfelled area are physical dams rather than stream power. The author believes that during periods of high precipitation, or rapid run off after snowmelt, the inability of these ditches to provide stable water courses could lead to the development of erosive overland flow and soil erosion in the main catchment of the Nant Tanllwyth. The possible benefits of log jams are discussed in Maitland *et al.* (1990) and seems to be with reference to when large volumes of sediment are liberated in poor working conditions. With the use of new guidelines seemingly halting the seriously destructive practices seen in the past, more care might now be appropriate in avoiding formation of log jams in small sub-tributaries.

6.3. Further Work

This work highlights the possibility of using a combination of techniques in two catchments to study the effects of timber harvesting on bedload transport in upland streams. It has, inevitably, highlighted weaknesses in approach and given rise to areas worthy of further research.

A limitation of any study involving a short time-period is the ability to quantify conditions before and after land use change to be able to disentangle the affects of the land use change itself. The study successfully quantifies the pattern in total bedload outputs using bedload traps, but unfortunately, it is believed that the bedload traps have a recording lag time too great to properly monitor the effects of land use change. A calculation of this lag (possibly by using tracers) and a longer study period might make bedload traps even more useful in monitoring the effects of harvesting.

The break up of the dam within the Afon Cyff is highlighted as being an important issue controlling sediment transfer in the channel. Unfortunately, despite significant efforts to obtain further detailed information on dates or circumstances of the dam break, it proved difficult to obtain concrete data. Further detailed historical accounts or sedimentary records of the channel would provide increased evidence for theories behind reduced sediment transfer in the Afon Cyff.

Photographic analysis of bed size distributions did not produce results anticipated and limits of resources made emptying traps at every visit impossible. The study therefore would have benefited from more reliable source of bedload grain size distributions for analysis. The possible improvements in bed photography were discussed in section 3.3, but a more successful ground truthing method, perhaps analysing individual clasts, is essential for using this method in future study. If resources allowed, excavations and sieving of a large sample of bedload trap material would also be beneficial. The samples would still need to be made using heavy plant for excavation and would still experience the wash through of fine sediment during passage through the deep water of the trap. However, a large sample would still be able to provide good data for each of the study periods and represent the actual transport of sediment through the reach during the period.

A better explanation of the increase in travel distances of tracers post-harvesting is required; it is thought that this explanation might be related to the size distributions of the bed. One of the major weaknesses of this study has been the inability to accurately monitor size distributions through the duration of fieldwork. Almost all of the methods considered were simply too destructive and would alter the transport mechanics that themselves were being examined. One possible solution would be a regular excavation and sieving of the end of channel bedload traps. As discussed previously, visual evidence from the Nant Tanllwyth suggested that a limited amount of sediment was released into the channel and material that was released would be unlikely to constitute bedload.

The use of a more advanced tracing technique is also more likely to better represent the real conditions of entrainment in both channels. It seems unlikely that the analysis showing that tracer burial depth had no influence on travel distance is not partially influenced by the excavation and attempted reburial of tracer clasts during searches. The destruction of the sediment matrix surrounding the tracer is unavoidable. Research using passive tracers with unique ID codes seeded in ditches of the Nant Tanllwyth is currently being undertaken (Stott, in prep). The development of this experiment, and any others associated with the brashings in the ephemeral tributaries of the Nant Tanllwyth, is an area that requires further research.

The influence of the release of sediment from the dam in the Afon Cyff is of significant interest to further investigation and future trapping and tracing study could examine the mechanics of bedload removal from large areas of deposited bedload after dam failure or mining deposits. Tracing would be particularly appropriate as there would be no requirement for tracers to be carefully seeded as the work would monitor one large shoal or sheet moving through the channel system. The changes in yields over time and with very large flood events might give estimates of the quantity of sediment a particular channel could absorb.

What still remains to be determined by future field observation is the proportion of time clasts spend undergoing "abrasion in place" processes (bed load over-passing, sandblasting and vibratory processes) compared to abrasion resulting from attrition (corner rounding, edge chipping and splitting) as clasts bounce or saltate during transport. Active (radio) tracer techniques as used by Schmidt and Ergenzinger (1992) during flood events may offer another means of isolating and determining the relative importance of these two sets of abrasion processes. However, techniques which rely on drilling clasts to insert magnets (as in this study), iron rods (Reid *et al.*, 1984) or radio tags inevitably will affect the strength of clasts and may render them more prone to breakage or splitting.

The long-term effects of the new harvesting techniques are now to be investigated with respect to bedload yields. With the long term cycle of the forest rotation, attention should inevitably consider the possible improvements to the second stage of the forest rotation, which has in the past had such dramatic effect on bedload yields. These results will most likely be derived from catchments with long-term sediment records, such as those at Plynlimon, a catchment with the longest detailed sediment record in the world. It would be short-sighted to neglect the value of such a record - which in turn provides a valuable future resource, for the sake of cost cutting in the short term.

Section 7: References

Adams, J. (1978) **Data for New Zealand pebble abrasion studies.** *New Zealand Journal of Science 21, 607-610.*

Adams, J. (1979) **Gravel size analysis from photographs.** *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 105, 1247-1255.*

Andrews, E.D and Smith, J.D. (1992) **A theoretical model for calculating marginal bedload transport rates of gravel.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester. 41-54.*

Arkell, B.P. (1985) **Magnetic tracing of fluvial sediments. A study with special emphasis on gravel bed rivers.** *PhD thesis, University of Liverpool.*

Arkell, B., Leeks, G., Newson, M. and Oldfield, F. (1983) **Trapping and tracing: some recent observations of supply and transport of coarse sediment from upland Wales.** *In: J.D. Collinson and J. Lewin (eds) Modern and Ancient - fluvial Systems. Blackwell Scientific Publications., Oxford. 107-119.*

Armanini, A. (1992) **Variation of bed and sediment load mean diameters due to erosion and deposition processes.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester. 351-362.*

Ashworth, P.J and Ferguson, R. I. (1989) **Size selective entrainment of bedload in gravel bed streams.** *Water Resources Research 25, 627-634.*

Ashworth, P.J., Ferguson, R.I., Ashmore, P.E., Paola, C. and Powell, D.M. (1992) **Measurements in braided river chute and Lobe. 2. Sorting of bed-load during entrainment, transport and deposition.** *Water Resources Research, 28, 1887-1896.*

Assani, A. A. and Petit, F. (1995) **Log-jam effects on bed mobility from experiments conducted in a small gravel-bed forest ditch.** *Catena 25, 117-126.*

Bagnold, R. A. (1980) **An empirical correlation of bedload transport rates in flumes and natural rivers.** *Proceedings of the Royal Society (London), Ser. A, 372, 453-473.*

Baker V.R. and Ritter D.F. (1975) **Competence of rivers to transport coarse bedload material.** *Bulletin of the Geological Society of America, 86, 975-978.*

Bellamy, K. (1992) **River morphology, sediments and fish habitats.** *Erosion and sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium, August 1992). International Association of Hydrological Sciences Publ. no. 210.*

Bennett, S.J. and Bridge, J.S. (1995) **An experimental study of flow, bedload transport and bed topography under conditions of erosion and deposition and comparison with theoretical models.** *Sedimentology, 42, 117-146.*

Bigelow, G. E. (1984) **Simulation of pebble abrasion on coastal beaches by transgressive waves.** *Earth Surface Processes and Landforms 9, 383-390.*

Bilby, R. E. (1984) **Removal of woody debris may affect stream channel stability.** *Journal of Forestry 85, 609-613.*

Billi, P. (1986) **Sediment storage, bed fabric and particles features of two mountain streams at Plynlimon (mid-Wales).** *Institute of Hydrology report no. 97.*

Binns, W.O. (1979) **The Hydrological effects of afforestation in Great Britain** *In: G. E. Hollis (ed). Man's impact on the hydrological cycle in the United Kingdom, Geo Abstracts Ltd, Norwich. 55-71.*

Binns, W.O (1986) **Forestry and fresh waters: problems and remedies.** *In: J. F de L. G. Solbe (ed). Effects of Land use on Fresh Waters, Ellis Horwood, Chichester. 364-377.*

Blackie, J.R. and Newson, M.D (1986) **The effects of forestry on the quantity and quality of runoff in upland Britain.** *In: J. F de L. G. Solbe (ed). Effects of Land use on Fresh Waters, Ellis Horwood, Chichester. 398-412.*

Bonnet, P.J.P., Leeks, G.J.L., and Cambray, R.S. (1989) **Transport processes for Chernobyl-labelled sediments; preliminary evidence from upland mid-Wales.** *Land Degradation and Rehabilitation. 1, 39-50.*

Bosch, J.M. and Hewlett, J.D. (1982) **A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration.** *Journal of Hydrology, 55, 3-23.*

Bradley, W.C. (1970) **Effect of weathering on abrasion of granitic gravel, Colorado River (Texas).** *Bulletin of the Geological Society of America, 81, 61-80.*

Bradley, W.C., Fahnestock, R.K. and Rowekamp, E.T. (1972) **Coarse sediment transport by flood flows on Knick River, Alaska.** *Bulletin of the Geological Society of America 83, 1261-1284.*

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

Brewer, P.A., Leeks, G.J.L., and Lewin, J. (1992) **Direct measurement of in-channel abrasion processes**. *In: Bogen, J. Walling, D. and Day, T.J. (eds.) Erosion and sediment transport monitoring programmes in river basins. International Association of Hydrological Sciences Publication 210, 21-30.*

Bridge, J.S. and Bennet, S.J. (1992) **A model for the entrainment and transport of sediment grains of mixed sizes, shapes, and densities.** *Water Resources Research, 28, 337-363.*

Briggs, D. (1977) **Sediments**. *Butterworths, London.*

Bryant, M.D. (1980) **Evolution of large organic debris after timber harvest: Maybeso Creek, 1949 to 1978.** *United States Department of Agriculture Forest Service General Technical Report PNW-101. Pacific Northwest Forest and Range Experimental Station, Portland, Oregon.*

Bryant, M.D. (1985) **Changes 30 years after logging in large woody debris and its use by salmonids.** *In: Johnson, R. R., Ziebell, C. D., Paton, D. R., Ffolloitt, P. F. and Hamre, R. H. (eds). Ecosystems and their Management: Reconciling Conflicting Uses. United States Department Agriculture, Forest Service General Technical Report, RM-120, 329-334.*

Bugosh, N. and Custer, S.G. (1989) **The effect of a log jam burst on bedload transport and channel characteristics in a headwater stream.** *In: Woessner, W. W. and Potts, D. F (eds). Proceedings of the Symposium on Headwater Hydrology. Missoula, MT, USA. 203-212.*

Bunte, K. (1992) **Particle number grain-size composition of bedload in a mountain stream.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester. 55-72.*

Bunte, K and Ergenzinger, P. (1989) **New tracer techniques for particles in gravel bed rivers.** *Bulletin de la Societe Geographique de Leige, 25, 85-90.*

Burt, T.P., Donahoe, M.A. and Vann, A.R. (1983) **The effect of forestry drainage operations on upland sediment yields: the results of a storm based study.** *Earth Surface Processes and Landforms 8, 339-346.*

Calder, I.R. (1986) **The influence of land use on water yield in upland areas of the U.K..** *Journal of Hydrology 88, 201-211.*

Carling, P.A. (1988) **The concept of dominant discharge applied to two gravel bed streams in relation to channel stability thresholds.** *Earth Surface Processes and Landforms, 13, 355-367.*

Carling, P.A. (1989) **Bedload transport in two gravel bedded streams.** *Earth Surface Processes and Landforms 14, 27-39.*

Carling, P.A. and Orr, H. (1990) **Response of benthic macroinvertebrates and salmonid fish in a Scottish stream to pre-afforestation drainage.** *Unpublished Report to the Atlantic Salmon Trust.*

Carling, P.A., Kelsey, A. and Glaister, M.S. (1992) **Effect of bed roughness, particle shape and orientation on initial motion criteria.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester. 23-40.*

Carling, P.A., Williams, J.J., Kelsey, A., Glaister, M.S. and Orr, H.G. (1998) **Coarse bedload transport in a mountain river.** *Earth Surface Processes and Landforms, 23, 141-157.*

Church, M.A. and Hassan, M.A. (1992) **Size and distance of travel of unconstrained clasts on a streambed.** *Water Resources Research 28, 299-303.*

Church, M.A., McLean, D.G. and Wolcott, J.F. (1987) **River bed gravels: Sampling and analysis.** *In: C.R. Thorne, J.C. Bathurst and R.D. Hey (eds). Sediment Transport in Gravel Bed Rivers. John Wiley and Sons, Chichester.*

Church, M.A., Wolcott, J.F. and Fletcher, K.W. (1991) **A test of equal mobility in fluvial sediment transport: behaviour of the sand fraction.** *Water Resources Research 27, 2941-2951.*

Clancy, J. (1991) **Site surveying and levelling.** *Edward Arnold, London.*

Clarke, R.T. and McCulloch, J.S.G. (1979) **The effect of land use on the hydrology of small upland catchments.** *In Hollis, G.E. (ed) Mans impact on the hydrological cycle in the United Kingdom. Geo Abstracts Ltd, Norwich.*

Crisp, D.T., Cubby, P.R. and Robson, S. (1980) **A survey of fish populations in the streams of the Plynlimon experimental catchments.** *Freshwater Biological Association, Teesdale Unit.*

Cuthbertson, R.H. (1948) **The present case for the afforestation of gathering grounds.** *Journal of the Institution of Water Engineers and Scientists, 2, 284-292.*

Daubree, A. (1879) **Etudes Synthetiques de Geologie Experimentale, 2 Volumes** *Dunod, Paris.*

Davis, R. J. and Gregory, K. J. (1994) **A new distinct mechanism of river bank erosion in a forested catchment.** *Journal of Hydrology, 157, 1-11.*

Dietrich, W. E., Dunne, T., Humphrey, N. F. and Reid, L. M. (1982) **Construction of sediment budgets for drainage basins** *In: F. J. Swanson, R. J. Janda, T. Dunne and D.N. Swanson (eds), Sediment budgets and routing in forested drainage basins. United States Department Agriculture Forest Service Publ. PNW-141, 5-23.*

Drew, I.B. (1992) **Bedload transport, vertical exchange and sediment storage in two Scottish Highland gravel-bed streams.** *PhD thesis, St Andrews University.*

Duck, R.W. and McManus, J. (1987) **Sediment yields in lowland Scotland derived from reservoir surveys.** *Transactions of the Royal Society of Edinburgh: Earth Sciences, 78, 369-377.*

Einstein, H.A. (1937) **Bedload transport as a probability problem.** *Ph. D Thesis. Published as Appendix C in Sedimentation, Shen, H. W. (ed) Colorado State University, Fort Collins, Colorado, USA.*

Einstein, H.A. (1950) **The bedload function for sediment transport in open channel flow.** *United States Department Agriculture Technical Bulletin, 1026.*

Ergenzinger, P. (1985) **Electromagnetic devices for measuring bedload transport.** *Sedimentology 32, 159.*

Ergenzinger, P. and Conrady, J. (1982) **A new tracer technique for measuring bedload in natural channels.** *Catena 9, 77-80.*

Ergenzinger, P., Schmidt, K-H. and Busskamp, R. (1989) **The pebble transmitter system (PETS): first results of a technique for studying coarse material erosion, transport and deposition.** *Zeitschrift für Geomorphologie, 33, 503-508.*

Fenton, J. and Abbott, J.E. (1977) **Initial movement of grains on a stream bed; the effect of relative protrusion.** *Proceedings of the Royal Society of London, Series A, 352, 523-537.*

Ferguson, R., Hoey, T., Wathen, S. and Werritty, A. (1996) **Field evidence for rapid downstream fining of river gravels through selective transport.** *Geology 24, 179-182.*

Ferguson, R.I. (1994) **Critical discharge for entrainment of poorly sorted gravel.** *Earth Surface Processes and Landforms, 19, 179-186.*

Ferguson, R.I. and Stott, T.A. (1987) **Forestry effects on suspended sediment and bedload yields in the Balquhidder catchments, Central Scotland.** *Transactions of the Royal Society of Edinburgh: Earth Sciences, 78, 379-384.*

Ferguson, R.I., and Wathen, S.J. (1998) **Tracer-pebble movement along a concave river profile: virtual velocity in relation to grain size and shear stress.** *Water Resources Research, 134, 2031-2038.*

Ferguson, R.I., Grieve, I.C. and Harrison, D.J. (1991) **Disentangling land use effects on sediment yield from year to year climatic variation.** *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation (Proceedings of the Vienna Symposium, August 1991), International Association of Hydrological Sciences Publication 203, 13-20.*

Ferguson, R.I., Stott, T.A. and Johnson, R.C. (1987) **Forestry and sediment yields in upland Scotland** *In: Erosion and Sedimentation in the Pacific Rim (Ed. by Beschta et al.), International Association Hydrological Science publ. 165, 499-500 (abstract). Poster presented at the above IAHS/IUFRO International Symposium on Erosion and Deposition in Forested Steeplands, Oregon State University, Corvallis, Oregon, USA, Aug. 1987.*

Forestry Commission (1993) **Forests and Water Guidelines** *HMSO, London.*

Fredriksen, R.L. (1970) **Erosion and sedimentation following road construction and timber harvest on unstable soils in three small western Oregon watersheds.** *United States Department of Agriculture Forest Service Research Paper PNW-104, Pacific NW Forest and Range Experimental Station, Portland, Oregon.*

Froehlich, W. and Starkel, L. (1987) **Normal and extreme monsoon rains-their role in shaping the Darjeeling Himalaya.** *Studia Geomorphologica Carpotha-Balcanica, 23, 105-12.*

Froehlich, W. and Starkel, L. (1993) **The effects of deforestation on slope and channel evolution in the tectonically active Darjeeling Himalaya.** *Earth Surface Processes and Landforms 18, 285-290.*

Frostick, L.E., Lucas, P.M. and Reid, I. (1984) **The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation.** *Journal of the Geological Society of London 141, 955-965.*

Gilbert, G.K. (1917) **Hydraulic-mining debris in the Sierra Nevada.** *United States Geological Survey Professional Paper 105.*

Gilvear, D.J. and Harrison, D.J. (1991) **Channel change and the significance of floodplain stratigraphy: 1990 flood event, lower River Tay, Scotland.** Earth Surface Processes and Landforms, Vol.16, 753-761.

Gintz, D and Schmidt, K.-H. (1991) **Grobgeschiebetransport in einem Gebirgsbach als Funktion von Gerinnebettform und Geschiebemorphometrie.** *Zeitschrift für Geomorphologie, Suppl. Bd.89, Berlin, Stuttgart. 71-78.*

Gomez, B. and Church, M. (1989) **An assessment of bedload sediment transport formulae for gravel-bed rivers**. *Water Resources Research,* 25, *1161-1186.*

Gomez, B. (1983) **Temporal variation in bedload transport rates: the effect of progressive bed armouring.** *Earth Surface Processes and Landforms, 8, 41-54.*

Gomez, B. (1991) **Bedload transport.** *Earth Science Reviews, 31, 89-132.*

Gomez, B. (1994) **Effects of particle-shape and mobility on stable armour development.** *Water Resources Research, 30, 2229-2239.*

Grant, G. E. and Wolff, A. L. (1991) **Long-term patterns of sediment transport after timber harvest, Western Cascade Mountains, Oregon, USA.** *In: Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation (Proceedings of the Vienna Symposium, August 1991), International Association of Hydrological Sciences Publication 203, 31-40.*

Harriman, R. and Morrison, B.R.S. (1982) **Ecology of streams draining forested and non-forested catchments in an area of central Scotland subject to acid precipitation.** *Hydrobiologia 88, 251-263.*

Harris, D.D. (1973) **Hydrologic changes after clearcut logging in a small Oregon coastal watershed.** *Journal Resources. United States Geological Survey, 1, 487-491.*

Harvey, A.M. (1987) **Sediment supply to upland streams: Influence on channel adjustment.** *In: C.R. Thorne, J.C. Bathurst and R.D. Hey (eds). Sediment Transport in Gravel Bed Rivers. John Wiley and Sons, Chichester, 121-150.*

Harvey, A.M. (1991) **The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, Northwest England.** *Earth Surface Processes and Landforms 16, 675-684.*

Hassan, M.A. (1990) **Scour, fill, and burial depth of coarse material in gravel bed streams.** *Earth Surface Processes and Landforms 15, 341-356.*

Hassan, M.A. and Church, M. (1992) **The movement of individual grains on the streambed.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., London. 159-176.*

Hassan, M.A., Church, M. and Ashworth, P.J. (1992) **Virtual rate and mean distance of travel of individual clasts in gravel-bed channels.** *Earth Surface Processes and Landforms 17, 617-627.*

Hassan, M.A., Church, M. and Schick, A.P. (1991) **Distance of movement of coarse particles in gravel bed streams.** *Water Resources Research 27, 503-511.*

Hassan, M. A., Schick, A. P. and Laronne, J. B. (1984) **The recovery of flood-dispersed coarse sediment particles - a three-dimensional magnetic tracing method.** *In: Schick, A. P. (ed) Channel Processes: Water, Sediment, Catchment Controls. Catena Supplement 5, 153-162.*

Haupt, H.F and Kidd, W.J. (1965) **Good logging practices reduce sedimentation in central Idaho.** *Journal of Forestry, 63, 664-670.*

Hedin, L.O., Mayer, M.S. and Likens, G.E. (1988) **The effect of deforestation on organic debris dams.** *Verh. Internat. Verein. Limnol. 23, 1135-1141.*

Hibbert, A.R. (1967) **Forest treatment effects on water yield.** *In: W.E. Sopper and H.W. Lull (eds). International Symposium on Forest Hydrology, Pergamon, Oxford. 813.*

Hoey, T. (1992) **Temporal variations in bedload transport rates and sediment storage in gravel-bed rivers.** *Progress in Physical Geography, 16, 319-338.*

Hubbell, D.W. and Sayre, W.W. (1964) **Sand transport studies with radioactive tracers.** *Proceedings of the American Society of Civil Engineers. Journal of Hydraulics Division, 90, 39-68.*

Huddart, D. (1994) **Rock-type controls on downstream changes in clast parameters in sandur systems in Southeast Iceland.** *Journal of Sedimentary Research, 64, 215-225.*

Johnson, R.C. (1990) **The interception, throughfall and stemflow in a forest in Highland Scotland and comparison with other upland forests in the U.K..** *Journal of Hydrology 118, 281-287.*

Johnson, R.C. (1991) **Effects of upland afforestation on water resources: the Balquhidder experiment 1981-1991.** *Institute of Hydrology report No. 16.*

Johnson, R.C. (1993) **Effects of forestry on suspended solids and bedload yields in the Balquhidder catchments.** *Journal of Hydrology 145, 403-417.*

Keller, E.A. and Swanson, F.J. (1979) **Effects of large organic material on channel form and fluvial processes.** *Earth Surface Processes 4, 361-380.*

Kirby, C., Newson, M.D. and Gilman, K. (1991) **Plynlimon research: The first two decades.** *Institute of Hydrology Report 109.*

Knighton, A. D. (1980) **Longitudinal changes in size and sorting of streambed material in four English rivers.** *Bulletin of the Geological Society of America, Part 1, 91, 55-62.*

Komar, P.D. and Carling, P.A. (1991) **Grain sorting in gravel-bed streams and the choice of particle sizes for flow-competence evaluations.** *Sedimentology, 38, 489-502.*

Komar, P.D. and Shih, S-M. (1992) **Equal mobility versus changing bedload grain sizes in gravel bed streams.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester, 73-108.*

Krumbein W.C. (1942) **Settling velocity and flume behaviour of non-spherical particles.** *Transactions of the American Geophysical Union, 23, 621-632.*

Kuenen, PH. H. (1956) **Experimental abrasion of pebbles: 2. Rolling by current.** *Journal of Geology 64, 336-368.*

Kuhnle, R.A. (1992) **Bedload transport during rising and falling stages on two small streams.** *Earth Surface Processes and Landforms 17, 191-197.*

Kuhnle, R.A. (1993) **Fluvial Transport of sand and gravel mixtures with bimodal size distributions.** *Sedimentary Geology, 85, 17-24.*

Kuhnle, R.A. and Southard, J.B (1988) **Bed-load transport fluctuations in a gravel bed laboratory channel.** *Water Resources Research, 24, 247-260.*

Laronne, J.B and Duncan, M.J. (1992) **Bedload transport paths and gravel bar formation.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester, 107-204.*

Law, F. (1956) **The effect of afforestation upon the yield of water catchment areas** *Journal of the British Waterworks Association 38, 484-494.*

Leeder (1983) **On the interactions between turbulent flow, sediment transport and bedform mechanics in channelized flows.** *In: J.D. Collinson and J. Lewin (eds). Modern and Ancient Fluvial Systems, Blackwell Scientific Publications., Oxford. 121-132.*

Leeks, G.J.L. (1992) **Impact of plantation forestry on sediment transport processes.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., Chichester, 651-670.*

Leeks, G.J.L. and Roberts, G. (1987) **The effects of forestry on upland streams - with special reference to water quality and sediment transport.** In: *Good, J.E.G. and Institute of Terrestrial Ecology (eds) Environmental aspects of plantation forestry in Wales, 9-24.*

Leeks, G.J.L, Lewin, J. and Newson, M.D. (1988) **Channel change, fluvial geomorphology and river engineering: The case of the Afon Trannon, mid-Wales.** *Earth Surface Processes and Landforms 13, 207-223.*

Leopold, L.B., Wolman, M.G. and Miller, J.P. (1964) **Fluvial processes in geomorphology.** *W.H. Freeman & Co., San Francisco.*

Lewis, A.B. and Neustein, S.A. (1971) **A preliminary study of soil erosion following clearfelling.** *Scottish Forestry 25, 121-125.*

Lisle, T.E. and Lewis, J. (1992) **Effects of sediment transport on survival of salmonid embryos in a natural stream: a simulation approach.** *Canadian Journal of Fisheries and Aquatic Sciences, 49, 2337-2344.*

Lovell, J. P. B., Ledger, D. C., Davies, I. M. and Tipper, J. C. (1973) **Rate of sedimentation in the North Esk reservoir, Midlothian.** *Scottish Journal of Geology 9, 57-61.*

Mackin, J.H. (1963) **Rational and empirical methods of investigation in Geology.** *In: C. C. Jr. Albritton (ed). Philosophy of Geohistory 1875-1970. Benchmark papers in Geology, 13, 135-163.*

Maitland, P.S., Newson, M.D. and Best, G.A. (1990) **The impact of afforestation and forestry practice on freshwater habitats.** *Focus on Nature Conservation Rep. 23, Nature Conservancy Council, Peterborough.*

Marks, S.D. (1996) **The impacts of particulate outputs associated with timber harvesting.** *Unpublished interim report, Institute of Hydrology, P2/i465/15.*

Marshall, P. (1927) **The wearing of beach gravels.** *Transactions and Proceedings, New Zealand Institute, 58, 507-532.*

Megahan, W. F. (1982) **Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith.** *In: F. J. Swanson, R. J. Janda, T. Dunne and D. N. Swanson (eds) Sediment budgets and routing in forested drainage basins United States Department of Agriculture Forest Service Publ., PNW-141, 114-121, Portland, OR. 114-121.*

Milhous, R.T. and Klingeman, P.C. (1973) **Sediment transport systems in a gravel bottomed stream**. *In. Hydraulic engineering and environment, Proceedings of the 21st Annual hydraulics Division speciality conference, American Society of Civil Engineers. Bozeman, Montana. 293-303.*

Mills, D.H (1979) **Downstream fining of pebbles - a quantitative review.** *Journal of Sedimentary Petrology,49,1, 295-302.*

Mills, D.H. (1980) **The management of forest streams.** *Forestry Commission Leaflet, 78, HMSO, London.*

Moffat, A.J. (1988) **Forestry and soil erosion in Britain - a review.** *Soil use and Management, 4, 41-44.*

Moog, D.B. and Whiting, P.J. (1998) **Annual hysteresis in bed load rating curves.** *Water Resources Research, 34, 2393-2399.*

Moore, R.J. and Newson, M.D. (1986) **Production, storage and output of coarse upland sediments: natural and artificial influences as revealed by research catchment studies.** *Journal of the Geological Society of London, 143, 1-6.*

Nanson, G.C. (1974) **Bedload and suspended-load transport in a small steep mountain stream.** *American Journal of Science 274, 471-486.*

Newson, M.D. (1975) **Plynlimon floods of August 5th/6th, 1973.** *Institute of Hydrology Report No. 26.*

Newson, M.D. (1976) **The physiography, deposits and vegetation of the Plynlimon experimental catchments.** *Institute of Hydrology Report No. 30.*

Newson, M.D. (1980a) **The erosion of drainage ditches and its effect on bedload yields in mid-Wales: Reconnaissance case studies.** *Earth Surface Processes 5, 275-290.*

Newson, M.D. (1980b) **The geomorphological effectiveness of floods- a contribution stimulated by two recent events in mid-Wales.** *Earth Surface Processes, 5, 1-16.*

Newson, M.D. and Calder, I.R. (1980) **The effects of afforestation on water resources in Scotland.** *In: Thomas M.F. and Coppock, J.T. (eds) Land assessment in Scotland. Aberdeen University Press.*

Newson, M. D. and Harrison, J. G. (1978) **Channel studies in the Plynlimon experimental catchments.** *Institute of Hydrology Report No. 47.*

Newson, M. D. and Leeks, G. J. H. (1987) **Transport processes at the regional scale: a regional study of increasing sediment yield and its effects in mid-Wales, U. K.** *In: C.R. Thorne, J.C. Bathurst and R.D. Hey (eds). Sediment Transport in Gravel Bed Rivers. John Wiley and Sons, Chichester. 187-224.*

Nicholas, A.P, Ashworth P.J, Kirkby, M.J., Macklin, M.G., and Murray, T. (1995) **Sediment slugs - large-scale fluctuations in fluvial sediment transport rates and storage volumes.** *Progress in Physical Geography, 19, 500-519.*

O' Loughlin, C.L., Rowe, L.K. and Pearce, A.J. (1978) **Sediment yields from small forested catchments, north Westland, Nelson, New Zealand.** *Journal of Hydrology (NZ), 17, 1-15.*

O' Loughlin, C.L., Rowe, L.K. and Pearce, A.J. (1980) **Sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand.** *In: The influence of man on the Hydrological Regime with Special Reference to Representative and Experimental Basins Symposium, International Association of Hydrological Sciences Publication 130, 285-293.*

Omerod, S.J. and Edwards (1985) **Stream acidity in some areas of Wales in relation to historical trends in afforestation and the usage of agricultural limestone.** *Journal of Environmental Management, 20, 189-197.*

Omerod, S.J. Tyler, S.J. and Lewis, M.J.S. (1987) **The influence of forest on aquatic fauna.** *In: Good, J.E.G. (ed) Environmental aspects of plantation forestry in Wales. Institute of Terrestrial Ecology, Grange-over-Sands. ITE symposium 22, 37-49.*

Painter, R.B., Blyth, K., Mosedale, J.C. and Kelly, M. (1974) **The effect of afforestation on erosion processes and sediment yield.** *In: Effects of Man on the Interface of the Hydrological Cycle with the Physical Environment. Proceedings of the Paris Symposium, Sept. 1974, International Association of Hydrological Sciences Publication 113, 62-67.*

Paola, C. and Seal, R. (1995) **Grain size patchiness as a cause of selective deposition and downstream fining.** *Water Resources Research, 31, 1395-1407.*

Parker, G. (1990) **Surface-based bedload transport relation for gravel river.** *Journal of Hydraulic Research, 28, 417-436*

Parker, G. and Klingeman, P.C. (1982) **On why gravel bed streams are paved.** *Water Resources Research, 18, 1409-1423.*

Parker, G. and Sutherland, A.J. (1990) **Fluvial Armour.** *Journal Of Hydraulic Research, 1990, 28, 529-544.*

Parker, G., Klingeman, P.C. and McLean, D.G. (1982) **Bedload and size distribution in paved gravel bed streams.** *Journal of the Hydraulics Division. ASCE, Vol. 108, HY4, 544-571.*

Petts, G.E. (1988) **Accumulation of fine sediment within substrate gravels along two regulated rivers, UK**. *Regulated Rivers: Research and Management, 2, 141-153.*

Petts, G.E. Thoms, M.C., Brittan, K. and Aitkin, B. (1989) **A freeze-coring technique applied to pollution by fine sediments in gravel bed rivers.** *The Science of the Total Environment, 84, 259-272.*

Powell, D.M. (1998) **Patterns and processes of sediment sorting in gravel-bed rivers.** *Progress in Physical Geography, 22, 1-32.*

Pritchett, W.L. and Fisher, R.F. (1987) **Properties and management of forest soils.** *John Wiley and Sons, New York.*

Reid, I., Brayshaw, A.C. and Frostick, L.E. (1984) **An electromagnetic device for automatic detection of bedload motion and its field applications.** *Sedimentology, 31, 269-276.*

Reid, I., Frostick, L.E. and Brayshaw, A.C. (1992) **Microform roughness elements and the selective entrainment and entrapment of particles in gravel bed rivers.** *In: P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi (eds) Dynamics of Gravel Bed Rivers. John Wiley & Sons Ltd., London. 253-276.*

Reid, I., Laronne, J.B., and Powell, D.M. (1998) **Flash-flood and bedload dynamics of desert gravel-bed streams.** *Hydrological Processes, 12, 543-557.*

Robinson, M. (1980) **The effect of pre-afforestation drainage in the streamflow and water quality of a small upland catchment.** *Institute of Hydrology Report, 73.*

Robinson, M. and Blyth, K. (1982) **The effects of forestry drainage operations on upland sediment yields: a case study.** *Earth Surface Processes and Landforms, 7, 85-90.*

Rothacher, J. (1970) **Increases in water yield following clear-cut logging in the Pacific Northwest.** *Water Resources Research, 6, 653-658.*

Sawyer, A.J., Leeks, G.J.L., Marks, S.D. and Stott, T.A. (1996) **The effects of timber harvesting on bedload flux dynamics: the application of an improved tracing technique in a small upland catchment.** *Geological Society of America AGM, 28-31 October 1996, Denver, Colorado, USA, Abstracts.*

Schmidt, K-H., and Ergenzinger, P. (1992) **Bedload entrainment, travel lengths, step lengths, rest periods-studied with passive (iron, magnetic) and active (radio) tracer techniques.** *Earth Surface Processes and Landforms 17, 147-165.*

Schumm, S.A. and Stevens, M.A. (1973) **Abrasion in place: A mechanism for rounding and size reduction of coarse sediments in rivers.** *Geology 1, 37-40.*

Shields, A. (1936) **Andvendung der Ähnlichkeitsmechanik ünd der turbulenz-forschung auf die geschiebebewegung.** *Mitteilung der preussischen versuchsanstalt für wasserbau und schiffbau. 26, Berlin*

Shih, S.M. and Komar, P.D (1990) **Differential bedload transport rates in a gravel-bed stream : a grain size distribution approach.** *Earth Surface Processes and Landforms, 15, 539-552.*

Smith, R.D., Sidle, R.C, Porter, P.E., and Noel, J.R. (1993) **Effects of experimental removal of woody debris on the channel morphology of a forest gravel bed stream.** *Earth Surface Processes and Landforms 18, 455-468.*

Soutar, R.G. (1989) **Afforestation, soil erosion and sediment yields in British freshwaters.** *Soil Use Management, 5, 82-86.*

Stoner, J.H. and Gee, A.S. (1985) **Effects of forestry on water quality and fish in Welsh rivers and lakes.** *Journal of the Institution of Water Engineers & Scientists, 39, 27-45.*

Stott, T.A. (1987) **Forestry effects on sediment sources, dynamics and yields in the Balquhidder catchments, central Scotland.** *Unpublished Ph.D. thesis, University of Stirling.*

Stott, T.A. (1996) **Changes in amount and size distribution of bedload trap material during forestry operations in central Scotland.** *In: Erosion and Sediment Yields: Global and Regional Perspectives - Poster Report Booklet edited by B. W. Webb, International Association of Hydrological Sciences Publication 236. Proceedings of a symposium held at Exeter, U.K., July 1996. 103-105.*

Stott, T. A. (1997a) **A Comparison of Stream Bank Erosion Processes on Forested and Moorland Streams in the Balquhidder Catchments, central Scotland.** *Earth Surface Processes and Landforms 22, 366-383.*

Stott, T.A. (1997b) **Forestry effects on bedload yields in mountain streams.** *Journal of Applied Geography, 17, 55-78.*

Stott, T.A. (1999) **Streambank and forest ditch erosion: Preliminary responses to timber harvesting in mid-Wales.** *In: A.G. Brown and T.A. Quine (eds) Fluvial Processes in Environmental Change. John Wiley & Sons, London. 47-70.*

Stott, T.A., Ferguson, R.I., Johnson, R.C. and Newson, M.D. (1986) **Sediment budgets in forested and unforested basins in upland Scotland.** *In: R.F. Hadley (ed) Drainage Basin Sediment Delivery. International Association of Hydrological Sciences Publication 159, 57-68.*

Stott, T.A. and Marks, S. (1998) **Bank erosion and suspended sediment dynamics: responses to timber harvesting in mid-Wales, U.K.** *Proceedings of the International Symposium on Comprehensive Watershed Management. 7-10 September 1998, Beijing, China.* ***213-220***

Stott, T.A. and Sawyer, A.J. (In press) **Clast travel distances and abrasion rates in two coarse upland channels determined using magnetically tagged bedload.** *In: Foster, I.D.L (ed) Tracers in Geomorphology, Wiley & Sons Ltd.*

Stretton, C. (1984) **Water supply and forestry - a conflict of interests: Cray Reservoir, a case study.** *Journal of the Institute of water engineers and scientists, 38, 323-330.*

Sutherland, A.J. (1987) **Static armour layers by selective erosion.** *In: C.R. Thorne, J.C. Bathurst and R.D. Hey (eds). Sediment Transport in Gravel Bed Rivers. John Wiley and Sons, Chichester, 243-267.*

Swanson, D. H. and Swanson, F. J. (1976) **Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest.** *In: D. R. Coates (ed) Geomorphology and Engineering. Dowden, Hutchinson & Ross Inc, 199-221.*

Takayama, S. (1965) **Bedload movement in torrential mountain streams.** *Tokyo Geography Papers, 9, 169-188 (in Japanese).*

Taylor, G.C.M. (1970) **Ploughing practice in the Forestry Commission.** *Forest Record 73, HMSO, London.*

Thoms, M.C. (1992) **A comparison of grab- and freeze-sampling techniques in the collection of gravel-bed river sediment.** *Sedimentary Geology, 78, 191-200.*

Thomson, D.A. (1979) **Forest drainage schemes.** *Forestry Commission Leaflet No. 72, HMSO, London.*

Thorne, C. R. and Lewin, J. (1979) **Bank processes, bed material movement and planform development in a meandering river.** *In: D.D. Rhodes and G. P. Williams (eds) Adjustments of the Fluvial System, Kendall/Hunt Publishing Co., Dubuque, Iowa, 117-137.*

Trimble, S.W. (1981) **Changes in sediment storage in the coon creek basin, driftless area, Wisconsin, 1853 to 1975.** *Science, 214, 181-183.*

Ursic, S.J. (1991) **Hydrologic effects of two method of harvesting mature Southern Pine.** *Water Resources Bulletin, 27, 303-315.*

Warburton, J. and Davies, T. (1994) **Variability of bedload transport and channel morphology in a braided river hydraulic model.** *Earth Surface Processes and Landforms 19, 403-421.*

Warburton J, and Demir, T (In press) **Influence of Bed Material Shape on Sediment transport in Gravel Bed Rivers: A field experiment.** *Tracers in Geomorphology, Wiley & Sons Ltd.*

Wathen, S.J. (1995) **The effect of storage sediment transfer processes in a small Scottish gravel-bed river.** *Unpublished Ph.D. thesis, St. Andrews.*

Wathen, S.J. and Hoey, T.B. (1998) **Morphological controls on the downstream passage of a sediment wave in a gravel-bed stream.** *Earth Surface Processes and Landforms, 23, 715-730.*

Wentworth, C.K. (1919) **A laboratory and field study of cobble abrasion.** *Journal of Geology, 27, 507-522.*

Whitaker, A.C. (1992) **An investigation into sediment stored behind dams of organic debris in small streams in an area of upland afforestation, central Scotland.** *Unpublished M.Sc. Thesis, University of Newcastle upon Tyne.*

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G. and Shreve, R.L. (1988) **Bedload sheets in heterogeneous sediments.** *Geology 16, 105-108.*

Wolman, M.G. (1954) **A method of sampling coarse river-bed material.** *Transactions of the American Geophysical Union 35, 951-956.*

Ziemer, R. R., Lewis, J., Lisle, T. E. and Rice, R. M. (1991) **Long-term sedimentation effects of different patterns of timber harvesting.** *In: Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation (Proceedings of the Vienna Symposium, August 1991) International Association of Hydrological Sciences Publication 203, 143-150.*

Zingg, T.H. (1935) **Beitrag zur Schotter analyse.** *Scheizerische Mineralogische und Petrographische Mitteilungen, 15, 39-140.*

Appendicies

Clast travel distances and abrasion rates in two coarse upland channels determined using magnetically tagged bedload

Paper to be submitted for BGRG Annual Conference 18th-20th September 1998: Tracers in Geomorphology, Coventry University.

'Clast travel distances and abrasion rates in two coarse upland channels determined using magnetically tagged bedload'

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INTRODUCTION

Downstream fining and rounding of clasts in rivers is well documented (McPherson, 1971; Mills, 1979; Knighton, 1980; Huddart, 1994; Ferguson *et al.*, 1996) and these changes in the sediment characteristics are commonly explained in terms of selective entrainment, transport, and deposition (hydraulic sorting), or the physical modification of clasts by mechanical abrasion. Such abrasion processes have been isolated in the past by use of abrasion tanks (Kuenen, 1956b; Bradley, 1970; Bradley *et al.*, 1972) and tumbling barrels (Daubree, 1879; Wentworth, 1919; Marshall, 1927; Bigelow, 1984). Under the laboratory conditions used by these workers, clast weight losses per unit distance were, however, consistently lower than downstream reductions in weight loss derived from field sampling (Bradley, 1970; Schumm and Stevens, 1973; Adams, 1978, 1979). The observed difference between laboratory simulated and field measured reduction rates have been attributed to either weathering (Bradley, 1970), hydraulic sorting processes (Mackin, 1963) or the alternative theory of 'abrasion in place' (Schumm and Stevens, 1973) whereby clasts may be abraded by vibration within the bed without net downstream movement. Laboratory simulation of this vibration yielded promising results. Brewer *et al.*, (1992) were the first to seed mobile and semi-mobile tracers to directly measure the abrasion of 39 individual test clasts in the natural environment. Weight losses sustained by tracers over a six week period indicated the potential of 'sandblasting' as an additional 'abrasion in place' process.

By introducing nearly four hundred magnetically tagged clasts into two natural channels and tracing their movements for over two years, we believe that this paper quantifies abrasion rates for individual test clasts in the natural field situation for the first time.

STUDY SITES

The study reaches were located within the Institute of Hydrology's Plynlimon Experimental Catchments (see Newson, 1976; Kirby *et al.*, 1991) which have been operational since 1968 and contain intensive hydrological, water quality and sediment monitoring networks (Leeks and Roberts, 1987; Leeks, 1992, Stott and Marks; 1998). The stream channels are influenced by both the local bed rock geology (Ordovician and Silurian mudstones and shales) and glacially derived gravels, cobbles and boulders. Much of the bedload is made up from this material and reworking of glacio-fluvial sediment of similar composition.

The climate is temperate with a mean annual precipitation of 2449 mm. Figure 1 shows the location of the catchments with the study reaches indicated. The catchment areas of the Tanllwyth (Severn) and Cyff (Wye) are 0.89 and 3.10 km^2 respectively and both channels are at a height of approximately 350 m A.O.D. The streams have flashy hydrographs and over the study period the maximum discharge reached 2.32 $m^3\ s^{-1}$ in the Tanllwyth channel with a mean of 0.06 $m^3\ s^{-1}$ over the period. There were an estimated 31 competent flood events and the time (in hours) when the discharge was greater than 1 $m^3\ s^{-1}$ (T>1) was 29; T > 0.5 $m^3\ s^{-1}$ = 190; T > 0.3 $m^3\ s^{-1}$ = 487.75.

METHODS

Tracer clasts were manufactured by drilling a hole and implanting a small magnet and label, fixed by epoxy resin. Only less resistant clasts of Silurian mudstone, shale and greywacke were soft enough to be drilled easily so this meant that glacially derived clasts of other geological origins were not included in the sample. A total of 385 tracers were made, clasts being sampled to represent the natural size distribution in the channels as closely as possible. Figure 2 shows the size distribution (% by weight) of tracers and natural bed material. The bed D_{50}s were 22.3 and 44.4 mm for the Tanllwyth and Cyff combined surface and sub-surface bed material respectively. Weighed tracers with a, b and c axes measured, were first introduced to the channels in February 1995. Tracers were dropped onto the bed and no special attempt was made to seed them. Groups of 10 tracers were placed in an equally spaced line across the channel. Tracers remained in the channel an average of 419 days (individual tracers ranging from 42 to 810 days) and their locations were surveyed on ten occasions between February 1995 and July 1997. The majority of tracers became buried after 1-2 months in the channel and on locating them they were dug out of the bed, identified and replaced into the hole from which they had been excavated. From these surveys total distance travelled by individual clasts was computed and clast dimensions and masses were re-measured in July 1997 as clasts were retrieved from the channel. At this point data for 228 clasts were available for analysis.

RESULTS

Clast abrasion rates (weight losses)

Table 1 shows summary statistics for all tracers, and for the tracers in the Tanllwyth and Cyff channels separately. Weight loss for individual tracers ranged from 0 to 57.17%, with a mean annual loss of 3.49±0.15%. The mean mass of all tracers introduced to the channels was 78.51 g and so this represents an actual mean weight reduction of 2.74 g per clast per year.

Figure 3 shows the variations in both weight loss and travel distance for clasts in the four Zingg shape classes. Clast shapes in the channels, and replicated in the sample of magnetically tagged tracers, were dominated by discs (48%)

and blades (42%), with rods (8%) and spheres (2%) relatively less common. Rod shaped clasts showed the greatest weight losses (5.38±0.66 %) and the difference between the weight loss of rods and blades is significant ($p < 0.05$) as shown by the t-test (Table 3). Though clasts in the forested Tanllwyth channel showed higher weight losses than those in the Cyff (moorland) channel, this difference is not statistically significant and may well be accounted for by the greater travel distances of all clasts in the Tanllwyth channel. Likewise, the greater weight losses of rod and sphere shaped clasts may be accounted for by their higher travel rates.

Figure 4 shows mean annual weight losses for tracers by their size class. Though the trend appears to show greatest weight losses in the -4.5 (16-22 mm) and -4.0 (11-16 mm) phi classes with a decrease in weight loss in the larger size classes, the small sample size in the -4.0 phi class (see Table 2) means this has large error bars. The only statistically significant differences between mean weight loss and clast size class was found in the coarser size classes where the weight loss in the -5.5 class was significantly greater than in the -6.0 phi class ($p < 0.01$) and weight loss in the -6.5 phi class was significantly greater than in the -6.0 phi class ($p < 0.05$) which are summarised in Table 3.

Travel Distances

The mean travel distance for all tracers was 0.11±0.02 m day^{-1} with a maximum travel rate of 0.87 m day^{-1}. Travel rates in the Tanllwyth (forested) channel were double those in the Cyff (moorland) and this difference is statistically significant as shown by the t-test in Table 3 ($p < 0.001$).

Figure 3 shows travel rates for the four shape classes. Rods and spheres showed greatest travel rates with means of 0.18±0.09 and 0.18±0.15 m day^{-1} respectively, though the small sample size for spheres means the estimate carries large error bars. Discs and blades had lower mean travel distances (0.11±0.03 and 0.10±0.03 m day^{-1} respectively) and the difference between the mean travel rate of discs and rods and between blades and rods were statistically significant as shown by the t-test ($p < 0.01$ for both shape classes) shown in Table 3.

Figure 4 indicates a general decrease in travel distance with increasing clast size and table 4 (correlation coefficients) supports this with the correlation between relative clast size (D_i/D_{50}) and average distance moved being -0.172, n. s. and -0.217, $p < 0.05$ for the Tanllwyth and Cyff tracers respectively.

Regression and Multiple Regression Analysis

The results of regression and multiple regression analysis are presented in Table 5. Data were plotted for each channel separately and in common with many previous tracer pebble studies produced a large amount of scatter. The data were $\log_{10}$ transformed and regressed both one variable at a time and then all three at once in multiple regression. Data from each channel were analysed separately. The results show that both tracer travel distance (m day^{-1}) and relative clast size (D_i/D_{50}) (where D_i is the clast b-axis and D_{50} is the combined bed surface and sub-surface mean grain size) were both useful predictors (statistically significant at $p < 0.01$ and $p < 0.025$ for the Cyff and Tanllwyth tracers respectively as shown by the F test) of % weight loss of clasts. Clast shape, as represented by the Krumbein Sphericity Index (Krumbein, 1941), was not a significant predictor in either channel. Using multiple regression the three independent variables explained 42.5 and 30.6% of the variation in clast weight loss in the Cyff and Tanllwyth channels respectively.

Table 6 shows the results of further investigations of how clast shape and size affect tracer travel distances. It can be seen that the proportion of variation in travel distance explained by sphericity and relative grain size (D_i/D_{50}) is maximised to 30.9 and 32.3% in the Cyff and Tanllwyth respectively by dividing sphericity by relative size to remove the effect of size. This suggests that clast shape (sphericity) does have a significant effect on travel distance after allowing for size ($p < 0.001$).

DISCUSSION

In terms of shape of clasts, rods and spheres have the highest mean travel distances, but while rods have highest weight losses, spheres have the lowest. This may be accounted for by the fact that their shapes make them more suited to rolling and, once in motion they are less likely to be deposited due to imbrication and bed armouring. Spheres, although uncommon in these channels, are nevertheless least likely to break while in transport and predictably their mean weight loss is lowest of the four shape classes. Rods, in contrast, are much more prone to breakage. Indeed, the maximum weight loss for all tracers was 57.17 % and this clast was a rod. If this particular clast is not considered, the mean weight loss for rods decreases to 3.85% and the next highest weight loss for rods is 13.02 % which implies that breakage of clasts is relatively unusual and that corner rounding and edge chipping are more likely to account for the weight losses observed.

The difference in weight loss between tracers in the Tanllwyth (forested) and the Cyff (moorland) channels is almost certainly accounted for by the greater mean travel distances and there is no reason to suspect, in the light of these data, that abrasion processes operating in each channel are different or operate in different ways. However, the greater production and transport of bedload in the Tanllwyth channel is discussed by Moore and Newson (1986) who report bedload yields from the Tanllwyth being six times higher than from the Cyff based on 10 years of records. They conclude that bedload yields from the forested Tanllwyth are more predictable, which reflects the greater importance of supply limited conditions on the grassland (unditched) Cyff catchment. The lower mean travel rates reported in this paper for the Cyff concur with these findings.

Correlations between variables as shown inTable 4 are weak but some are nevertheless statisticallysignificant. The correlation between size and distance travelled is significant in the Cyff ($p < 0.05$) only giving some evidence for size selective transport in this channel where bedload seems to be supply limited. The extent and nature of this is the subject of further analysis (Sawyer, in prep).

Regression and multiple regression have been partially successful in explaining % weight losses in terms of travel distance, particle shape (Krumbein's Sphericity Index) and relative clast size (D_i/D_{50}). Multiple regression was able to explain 42.5 and 30.6 % of the variation in tracer % weight loss in the Cyff and Tanllwyth respectively suggesting that other factors such as the precise geological composition of the clasts are almost certainly important in predicting abrasion rates. In regression analysis the least useful predictor was sphericity which was not statistically significant in either channel, whereas travel distance and relative size (D_i/D_{50}) were both statistically significant ($p < 0.01$ in Cyff; $p < 0.025$ in Tanllwyth).

In contrast to the "abrasion in place" processes (bed load over-passing and sandblasting) monitored in the Tanllwyth channel by Brewer *et al.* (1992) and distinguished from the "vibratory" processes proposed by Schumm and Stevens (1973), the findings of this study demonstrate that the abrasion rate of natural tracers is dependent upon clast size and travel distance, with shape being of secondary importance. What still remains to be determined by future field observations is the proportion of time clasts spend undergoing "abrasion in place" processes (bed load over-passing, sandblasting and vibratory processes) compared to abrasion resulting from attrition (corner rounding and egde chipping) as clasts bounce or saltate during transport. Active (radio) tracer techniques as used by Schmidt and Ergenzinger (1992) during flood events may be one way of isolating and determining the relative importance of these two sets of abrasion processes.

CONCLUSIONS

1 The mean travel distance for tracers in the forested Tanllwyth channel (0.14 ± 0.03 m day^{-1}) was double that for the Cyff (0.07 ± 0.03 m day^{-1}) (with the difference significant at $p < 0.001$ level), while mean weight losses for each channel of 4.15 ± 0.24 and 2.83 ± 0.18 % respectively suggest processes such as corner rounding and edge chipping to be the dominant abrasion process with some examples of breakage (57.17% weight loss) occurring.

2 In general higher abrasion rates are attributed to greater travel distances, though for some of the coarser clasts this is not so. The data provide evidence for a link between clast size and abrasion rate. Significant differences in weight loss were found between size classes in the coarser size fractions which cannot be easily explained in terms of different travel distances. This suggests that 'abrasion in place' or 'sandblasting' processes may be operating.

3 Clast shapes in the channels, and replicated in the sample of magnetically tagged tracers, were dominated by discs (48%) and blades (42%) with rods (8%) and spheres (2%) relatively less common. Rods showed the highest abrasion rates with clasts losing a mean of 5.38 ± 0.66 % of their mass per year. In terms of shape, the highest mean travel rates recorded were for rods (0.81 ± 0.09 m day^{-1}) and spheres (0.81 ± 0.15 m day^{-1}), whereas discs and blades travelled 0.11 ± 0.03 and 0.12 ± 0.05 m day^{-1} respectively. Only the difference between the travel rate of rods and blades was significant as determined by the *t*-test ($p < 0.05$).

4 Regression and multiple regression have been partially successful in explaining % weight losses in terms of travel distance, particle shape (Krumbein's Sphericity Index) and relative clast size (D_i/D_{50}). Multiple regression was able to explain 42.5 and 30.6 % of the variation in tracer % weight loss in the Cyff and Tanllwyth respectively. The least useful predictor was sphericity which was not statistically significant in either channel, whereas travel distance and relative size (D_i/D_{50}) were both statistically significant ($p < 0.01$ in Cyff; $p < 0.025$ in Tanllwyth).

5 Relationships between clast size and travel distance were demonstrated for both the Cyff ($p < 0.01$) and Tanllwyth ($p < 0.025$) suggesting that size selective transport of bed material is operating to a greater extent in the grassland Cyff channel, which is sediment supply limited, than in the forested and ditched Tanllwyth where the bedload yield is up to six-times greater. Travel distances in the Tanllwyth channel (where the catchment is forested) are double those in the grassland Cyff. The higher transport rates in the Tanllwyth channel can tentatively be used to explain the higher mean abrasion rate of the tracers in that channel. However, the link is not proven and further research, possibly using active (radio) tracers for example, may allow the relative importance of "abrasion in place" and attrition in transport (corner rounding or edge chipping) to be determined.

6 These findings have significance for helping to explain observed downstream fining and trends in bed sediment character of alluvial channels, the production of fines from in-channel abrasion processes and they add significantly to a relatively small dataset from which natural in-channel abrasion rates may be assessed. Consideration should be given to including them as a component in models which attempt to predict downstream changes in shape and size as well as the production of fines from abrasion processes.

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REFERENCES

Adams, J. (1978) 'Data for New Zealand pebble abrasion studies', New Zealand Journal of Science 21, 607-610.

Adams, J. (1979) 'Gravel size analysis from photographs'. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 105, 1247-1255.

Bigelow, G. E. (1984) 'Simulation of pebble abrasion on coastal benches by transgressive waves', Earth Surface Processes and Landforms 9, 383-390.

Bradley, W.C. (1970) 'Effect of weathering on abrasion of granitic gravel, Colorado River (Texas)', Geological Society of America Bulletin 81, 61-80.

Bradley, W.C., Fahnestock, R. K. and Rowekamp, E. T. (1972) 'Coarse sediment transport by flood flows on Knick River, Alaska', Geological Society of America Bulletin 83, 1261-1284.

Brewer, P.A., Leeks, G.J.L, and Lewin, J. (1992) 'Direct measurement of in-channel abrasion processes', in Bogen, J., Walling, D. E. and Day, T. (Eds) Erosion and Sediment Transport Monitoring in River Basins (Proceedings of the Oslo Symposium 24-28 August 1992), International Association of Hydrological Sciences Publication 210, 21-29.

Daubree, A. (1879) 'Etudes Synthetiques de Geologie Experimentale. 2 Volumes, Dunod, Paris.

Ferguson, R., Hoey, T., Wathen, S. and Werritty, A. (1996) 'Field evidence for rapid downstream fining of gravels through selective transport', Geology 24, 179-182.

Huddart, D. (1994) 'Rock-type controls on downstream changes in clast parameters in sandur systems in Southeast Iceland', Journal of Sedimentary Research, 64 (2), 215-225.

Kirby, C., Newson, M. D. and Gilman, K. (1991) 'Plynlimon research: The first two decades', Institute of Hydrology Report 109, 188pp.

Knighton, A. D. (1980) 'Longitudinal changes in size and sorting of streambed material in four English rivers', Geological Society of America Bulletin. Part 1, 91, 55-62.

Krumbein, W. (1941) 'Measurement and geological significance of shape and roundness of sedimentary particles', Journal of Sedimentary Petrology 11, 64-72.

Kuenen, PH. H. (1956b) 'Experimental abrasion of pebbles: 2. Rolling by current', Journal of Geology 64, 336-368.

Leeks, G.J.L. (1992) 'Impact of plantation forestry on sediment transport processes', in Dynamics of Gravel Bed Rivers. Ed. by P. Billi, R.D. Hey, C.R. Thorne & P. Tacconi. John Wiley & Sons Ltd., Chichester, 651-670.

Leeks, G.J.L. and Roberts, G. (1987) 'The effects of forestry on upland streams with special reference to water quality and sediment transport', in Good, J.E.G. and Institute of Terrestrial Ecology (eds), 1987, Environmental aspects of plantation forestry in Wales. No. 22, 9-24. Grange -over-Sands, Institute of Terrestrial Ecology, Merlewood Research Station.

Mackin, J. H. (1963) 'Rational and empirical methods of investigation in

Geology', in Philosophy of Geohistory 1875-1970 (ed. by C. C. Jr. Albritton). Benchmark papers in Geology, 13, 135-163.

Marshall, P. (1927) 'The wearing of beach gravels', Transactions and Proceedings . New Zealand Institute, 58, 507-532.

McPherson, H. J. (1971) 'Downstream changes in sediment characteristics in a high energy mountain stream channel', Arctic and Alpine Research, 3, 65-79.

Mills, H.H. (1979) 'Downstream fining of pebbles-a quantitative review', Journal of Sedimentary Petrology, 49 (1), 295-302.

Moore, R.J. and Newson, M.D. (1986) 'Production, storage and output of coarse upland sediments: natural and artificial influences as revealed by research catchment studies', Journal of the Geological Society, 143, 1-6.

Newson, M.D. (1976a) 'The physiography, deposits and vegetation of the Plynlimon experimental catchments'. Institute of Hydrology Report 30, 54pp.

Sawyer, A. (in prep) 'Forestry effects on sediment storage, routing and abrasion in upland streams', PhD Thesis, Liverpool John Moores University.

Schmidt, K-H., and Ergenzinger, P. (1992) 'Bedload entrainment, travel lengths, step lengths, rest periods-studied with passive (iron, magnetic) and active (radio) tracer techniques', Earth Surface Processes and Landforms 17, 147-165.

Schumm, S.A. and Stevens, M. A. (1973) 'Abrasion in place: A mechanism for rounding and size reduction of coarse sediments in rivers', Geology 1, 37-40.

Stott, T. A. and Marks, S. (1998) 'Bank erosion and suspended sediment dynamics: responses to timber harvesting in mid Wales, UK', International Symposium on Comprehensive Watershed Management (ISWM-'98), 7-10 September 1998, Beijing, China.

Wentworth, C. K. (1919) 'A laboratory and field study of cobble abrasion', Journal of Geology, 27, 507-522.

Figure 1: Location map to show study reaches.

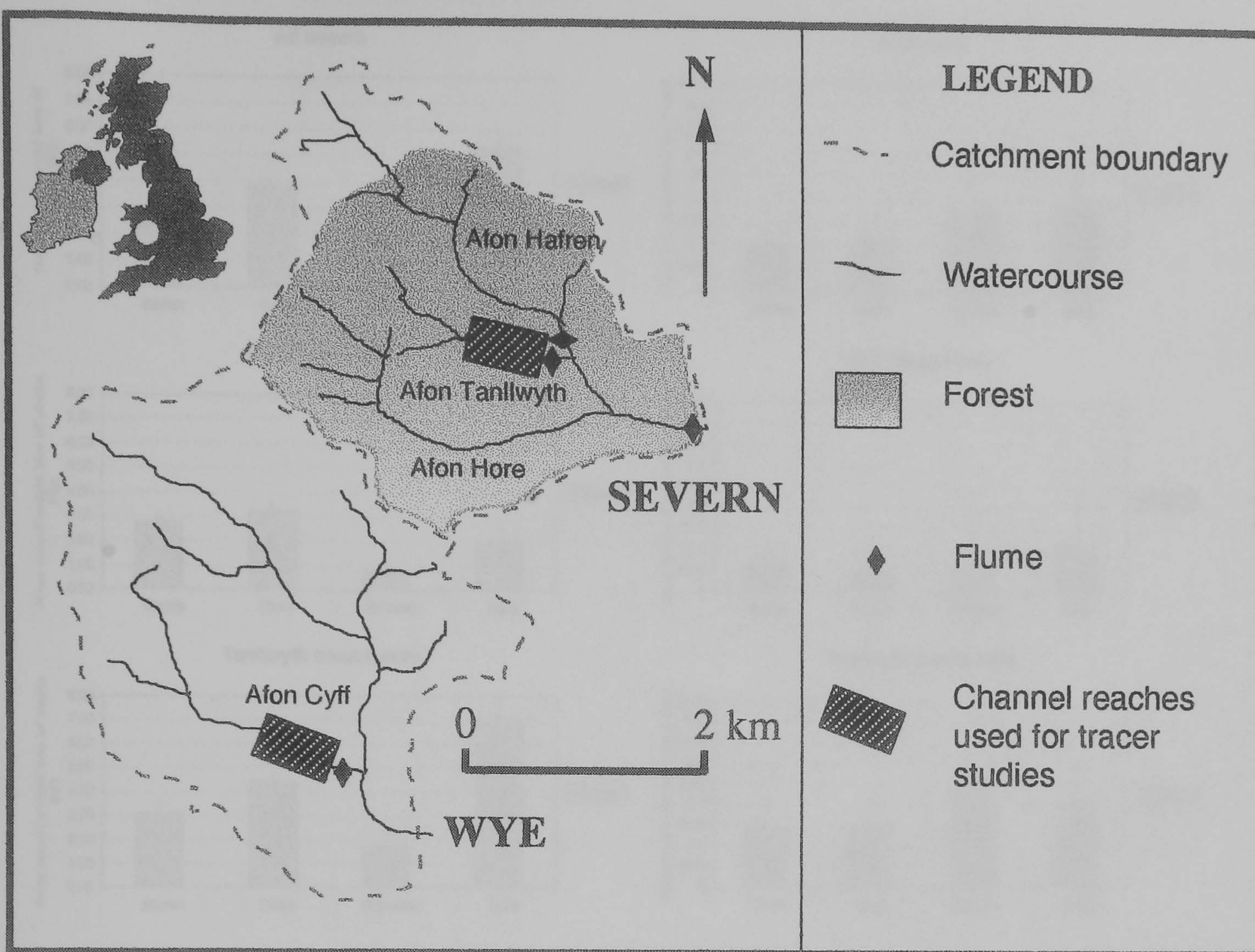

Figure 2: Size distributions of tracers and natural bed material
(a) Tanllwyth bed material (after Brewer *et al.*, 1992), (b) all tracers, (c) Tanllwyth tracers only, (d) Cyff tracers only. Bed D_{50} s are 22.3 and 44.4 mm for Tanllwyth and Cyff channels respectively.

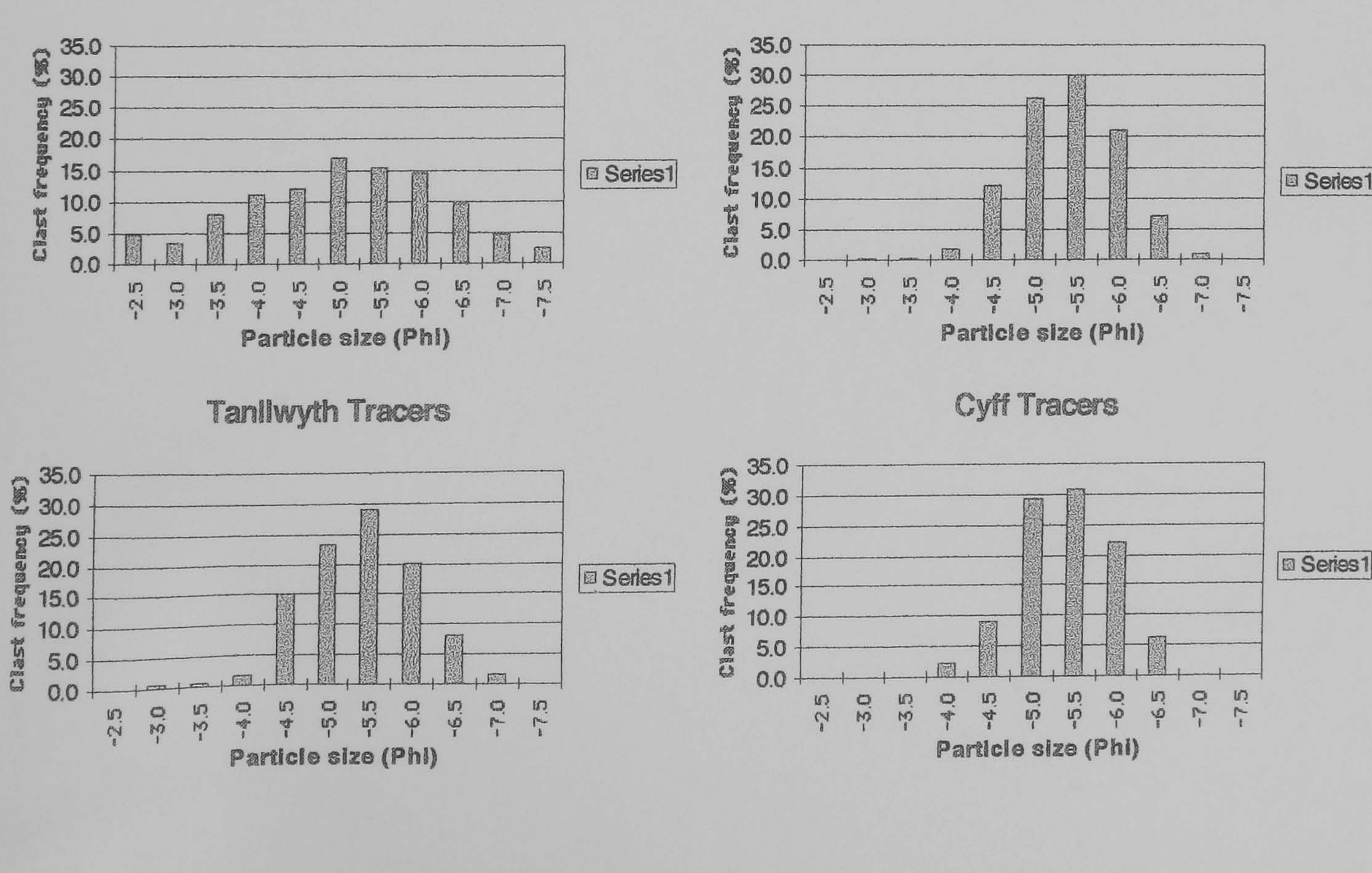

Figure 3: Analysis by shape: weight loss of tracers and distance travelled for all tracers, Cyff only and Tanllwyth only.

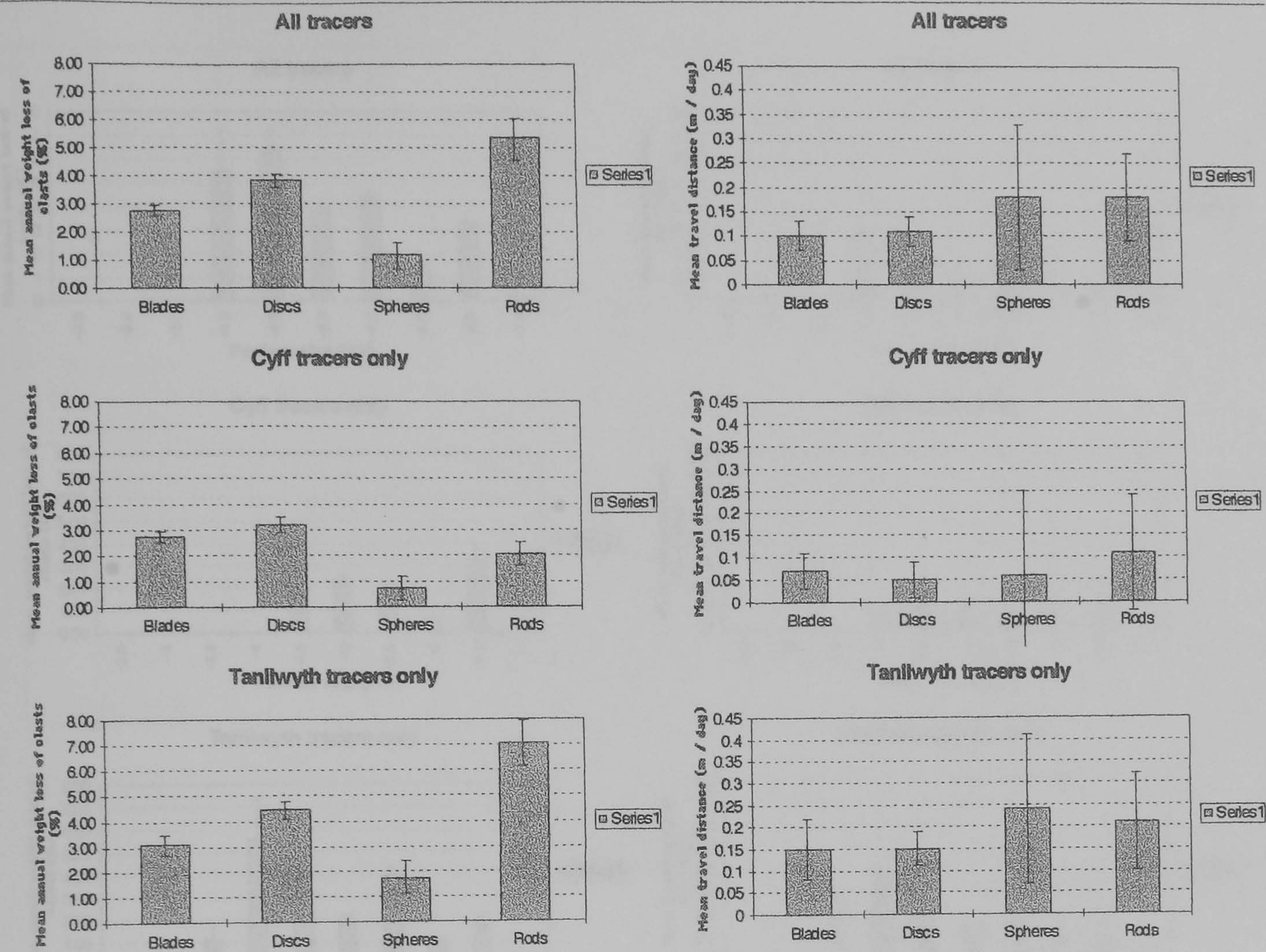

Figure 4: Analysis by size: weight loss of tracers and distance travelled for all tracers, Cyff only and Tanllwyth only.

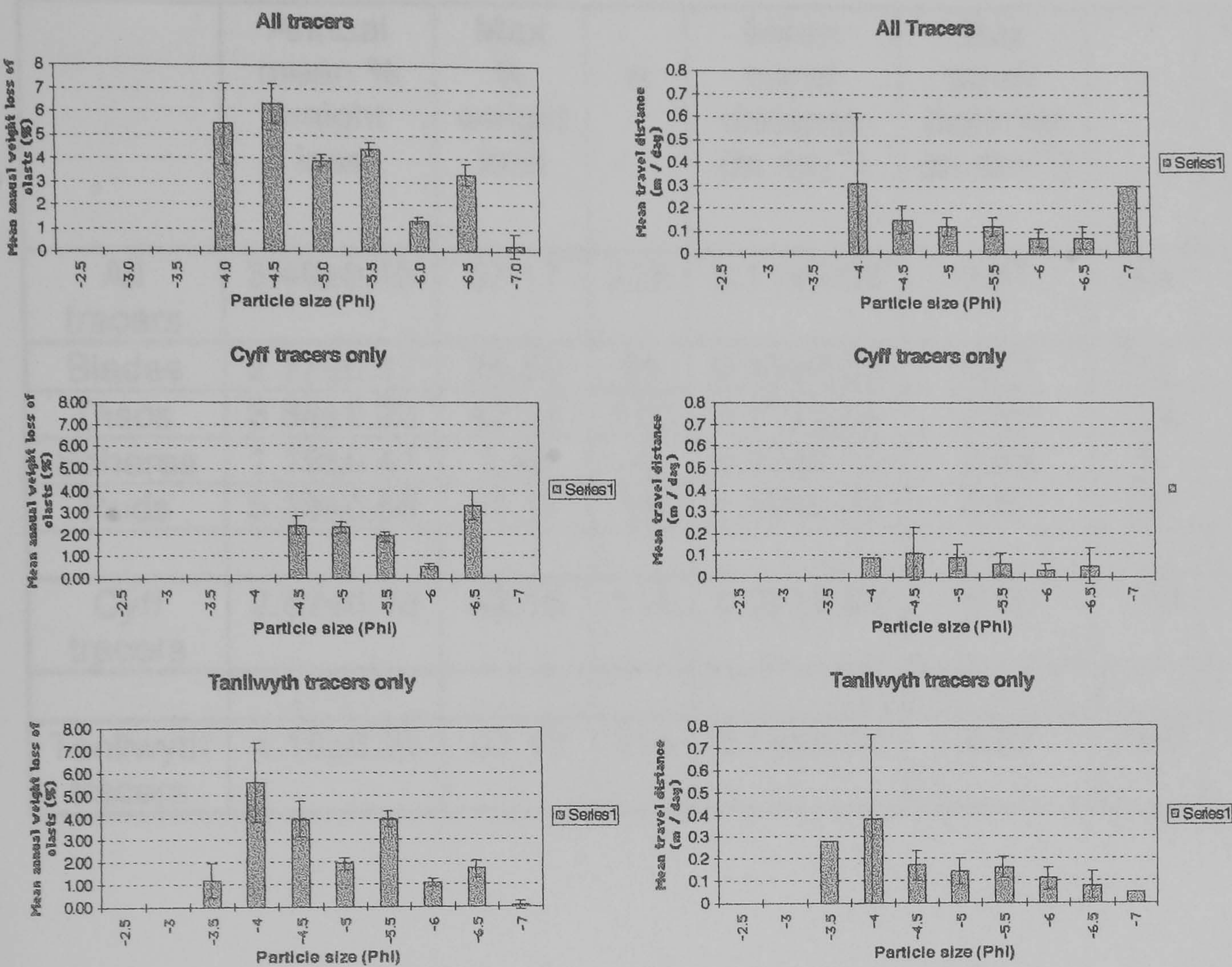

Table 1: Summary statistics for tracer abrasion (% weight loss) and travel distances for all tracers, separated by shape and for Cyff and Tanllwyth channels separately.

	Annual mean % weight loss	Max % weight loss	n	Mean travel distance (m day^{-1})	Max travel distance (m day^{-1})	n	Mean no. days in channel
All tracers	3.49±0.15	57.17	228	0.11±0.02	0.87	284	411
Blades	2.77±0.17	24.50	95	0.10±0.03	0.73	117	402
Discs	3.84±0.23	42.15	110	0.11±0.03	0.50	136	411
Spheres	1.19±0.41	2.48	4	0.18±0.15	0.39	6	450
Rods	5.38±0.66	57.17	19	0.18±0.09	0.87	25	451
Cyff tracers	2.82±0.18	42.15	114	0.07±0.03	0.43	119	423
Tanllwyth tracers	4.15±0.24	57.17	114	0.14±0.03	0.87	165	404

Table 2: Summary statistics for tracer abrasion (% weight loss or %WL) and travel distances for all tracers, separated by size class.

Phi Size	Annual mean % weight loss	Max % weight loss	n	Mean travel distance (m day^{-1})	Max travel distance (m day^{-1})	n	Mean no. days tracers in channel
-4.0	5.46±1.74	6.85	3	0.31±0.31	0.87	3	224
-4.5	6.33±0.85	57.17	24	0.15±0.06	0.73	35	292
-5.0	3.90±0.26	23.26	56	0.12±0.04	0.50	78	356
-5.5	4.40±0.29	41.18	76	0.12±0.04	0.45	85	385
-6.0	1.33±0.14	1.96	47	0.07±0.04	0.38	58	538
-6.5	3.33±0.46	5.23	20	0.07±0.05	0.19	22	574
-7.0	0.22±0.52	0.30	1	0.30±0.30	0.30	1	507

Table 3: Significant t-test results for tracer weight loss (%WL) and distance moved for different shape and size classes.

Tracers	Mean	n	Tracers	Mean	n	t-statistic	t-critical	Significance level
Weight losses (mean % per year)								
-5.5	3.04	116	-6.0	1.14	81	2.58	1.97	$p < 0.01$
-6.0	1.14	81	-6.5	3.73	28	-2.47	1.98	$p < 0.05$
All blades	2.77	74	All rods	5.38	19	-1.99	1.98	$p < 0.05$
Travel Distances (mean m day^{-1})								
All Cyff tracers	0.07	119	All Tanllwyth tracers	0.14	165	-5.62	1.96	$p < 0.001$
All blades	0.10	85	All rods	0.18	25	-2.69	1.98	$p < 0.01$
All discs	0.11	136	All rods	0.18	25	-2.72	1.97	$p < 0.01$
-4	0.31	4	-5.0	0.12	78	2.47	1.99	$p < 0.05$
-4	0.31	4	-5.5	0.12	78	2.63	1.99	$p < 0.01$
-4	0.31	4	-6.0	0.07	58	4.14	2.00	$p < 0.001$
-4	0.31	4	-6.5	0.07	22	3.06	2.06	$p < 0.01$
-4.5	0.15	35	-6.0	0.07	58	3.64	1.98	$p < 0.001$
-5.0	0.12	78	-6.0	0.07	58	2.74	1.97	$p < 0.01$
-5.5	0.12	78	-6.0	0.07	58	3.04	1.97	$p < 0.01$
-5.5	0.12	78	-6.5	0.07	22	2.14	1.98	$p < 0.05$

Table 4: Correlation coefficients for tracers: % weight loss, distance moved, shape and size indices, with statistical significance indicated: * $p > 0.05$; ** $p > 0.01$. NB. Data are Log_{10} transformed.

CYFF	Average distance moved (m / day)	Krumbein's Sphericity Index	Relative clast size D_i/D_{50}
% weight loss	**0.316 ** **	**-0.145**	**-0.332 ** **
Average distance moved (m / day)		**-0.006**	**-0.217 * **
Krumbein's Sphericity Index			**0.219 * **
TANLLWYTH			
% weight loss	**0.229 * **	**0.101**	**-0.219 * **
Average distance moved (m / day)		**0.211 * **	**-0.172**
Krumbein's Sphericity Index			**0.120**

Table 5: Regression and Multiple Regression Analyses: factors affecting % weight loss (%WL) of tracers.

	CYFF					
	Regression	Multiple R	v_1	v_2	F	Significance F
1	Log_{10} %WL vs Log_{10} distance	31.6	1	77	8.45	$p < 0.01$
2	Log_{10} %WL vs Log_{10} sphericity	14.5	1	77	1.64	n.s.
3	Log_{10} %WL vs Log_{10} D_i/D_{50}	33.2	1	77	9.46	$p < 0.01$
	Multiple Regression					
4	Log_{10} %WL vs Log_{10} distance, Log_{10} sphericity, Log_{10} D_i/D_{50}	42.5	3	77	5.43	$p < 0.01$
	TANLLWYTH					
	Regression					
5	Log_{10} %WL vs Log_{10} distance	22.9	1	105	5.79	$p < 0.025$
6	Log_{10} %WL vs Log_{10} sphericity	10.1	1	105	1.08	n.s.
7	Log_{10} %WL vs Log_{10} D_i/D_{50}	21.9	1	105	5.28	$p < 0.025$
	Multiple Regression					
8	Log_{10} %WL vs Log_{10} distance, Log_{10} sphericity, Log_{10} D_i/D_{50}	30.6	3	105	3.50	$p < 0.025$

v_1 and v_2 are upper and lower d.f respectively.

Table 6: Regression analysis results of factors affecting tracer travel distance.

	Regression					
	CYFF	Multiple R	v_1	v_2	F	Significance F
1	Distance vs sphericity	2.6	1	118	0.08	n.s.
2	Distance vs Di/D_{50}	27.1	1	118	9.26	$p < 0.01$
3	Distance vs (sphericity / D_i/D_{50})	30.9	1	118	12.34	$p < 0.001$
	TANLLWYTH					
4	Distance vs sphericity	21.5	1	164	7.91	$p < 0.01$
5	Distance vs Di/D_{50}	24.6	1	164	10.58	$p < 0.01$
6	Distance vs (sphericity / D_i/D_{50})	32.3	1	164	18.98	$p < 0.001$

v_1 and v_2 are upper and lower d.f respectively.