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Significance of Bedrock Channel Morphology and Sediment Dynamics in a U.K. Upland River.

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28 FEB [illegible]

Abstract

Bedrock channels in the uplands of the U.K. are widespread but their geomorphology and sedimentology have rarely been studied. The aim of this research is to determine rates and processes of sedimentation in an upland bedrock channel following a large flood event. The main field site is a 300 m bedrock reach of Trout Beck in the Upper Tees drainage basin, Northern England. Sedimentary processes are investigated using morphological evidence (channel cross section surveys, repeat photography and geomorphic mapping) and field tracing of coarse bedload. The significance of the channel processes operating in the study reach are evaluated by mapping the extent of bedrock channel features in the upper Tees catchment. Flume experiments are also undertaken to supplement field data collected in rock step surveys.

In the Upper Tees catchment, bedrock channels form 20% of the upland stream network, 10% of channels consist of bare rock with no sedimentation. The stream network was divided into five channel classes from bedrock (1) through to fully alluvial (5). In both Trout Beck and the Upper Tees bedrock channel sections gradual transitions from bedrock to fully alluvial reaches and back again were common. Equally, however very abrupt changes at the end of fully alluvial or bedrock channel section could often be found (e.g. transitions 1-5 and 5-1). Classification of the river channel using this scheme allowed the local importantance of bedrock channel landforms on hydraulic conditions and sedimentation processes to be described.

In the study reach both lateral sedimentation and amalgamation of sediment bars were observed as mechanisms of re-sedimentation. The rate and location of sedimentation is controlled by local hydraulics (rock steps), gradient and discharge. The tracer study supports the assumption that sediment movement in river channels is episodic. The rock step survey demonstrated the large variability in the shape and size of these features and their important influence on the hydraulics of the flow.

Acknowledgements

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Declaration

I declare that none of the material included in this thesis has previously been submitted for any other degree at any other university.

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Chapter 1 – Introduction and Study Area

1.1 Introduction

This chapter describes the aims and objectives of the research and provides an account of the study area. There is a description of the local river systems and geology of the area and a brief account of the soil type and vegetation. The landscape evolution is examined, in particular the effects of past glaciation, mining and agriculture. The chapter also reviews the processes of river development and the influence of climate within the study area.

1.2 Background

This research is focused on bedrock channels, until the last decade very little research had been conducted on bedrock channels (Tinkler and Wohl 1998). Although bedrock channels form a specific area of fluvial geomorphology they show a great variety of forms and can be found in an array of different environments and geological settings. It has been shown that an understanding of alluvial and gravel channels is not easily transferred to bedrock because of significant differences in hydraulic geometry (Tinkler and Wohl, 1998). The lack of research in this area is surprising considering the frequent occurrence of this type of channel throughout the world. This is especially true in a U.K. context, where virtually no research has been conducted on these channels despite widespread occurrence of bedrock channels in the uplands. This research aims to rectify this in a small way by: (1) providing a new classification scheme for bedrock channels in an upland river system and (2) documenting temporal and spatial changes in the sediment balance of a bedrock channel reach flowing a major flood event.

1.3. Aim

The primary aim of this research is to determine rates and processes of sedimentation in an upland bedrock channel following a large flood event.

This is estimated using morphological evidence (from channel cross surveys, repeat photography and geomorphic mapping) and field tracing of coarse bedload movement. The significance of processes operating in the chosen study reach is evaluated by mapping the extent of bedrock channel features in the wider catchment. This is carried out in the upper Tees catchment in the North Pennines, Northern England. A small bedrock study reach on Trout Beck a tributary of the Tees was selected for detailed study.

1.4. Objectives

- To establish rates and processes of sedimentation in a bedrock channel reach, based on morphological evidence measured from channel cross section data and changes in sediment surface grain–size along cross channel transects.

- To determine spatial patterns of sedimentation over the study reach and demonstrate change in sediment storage in a bedrock channel after a large flood event.

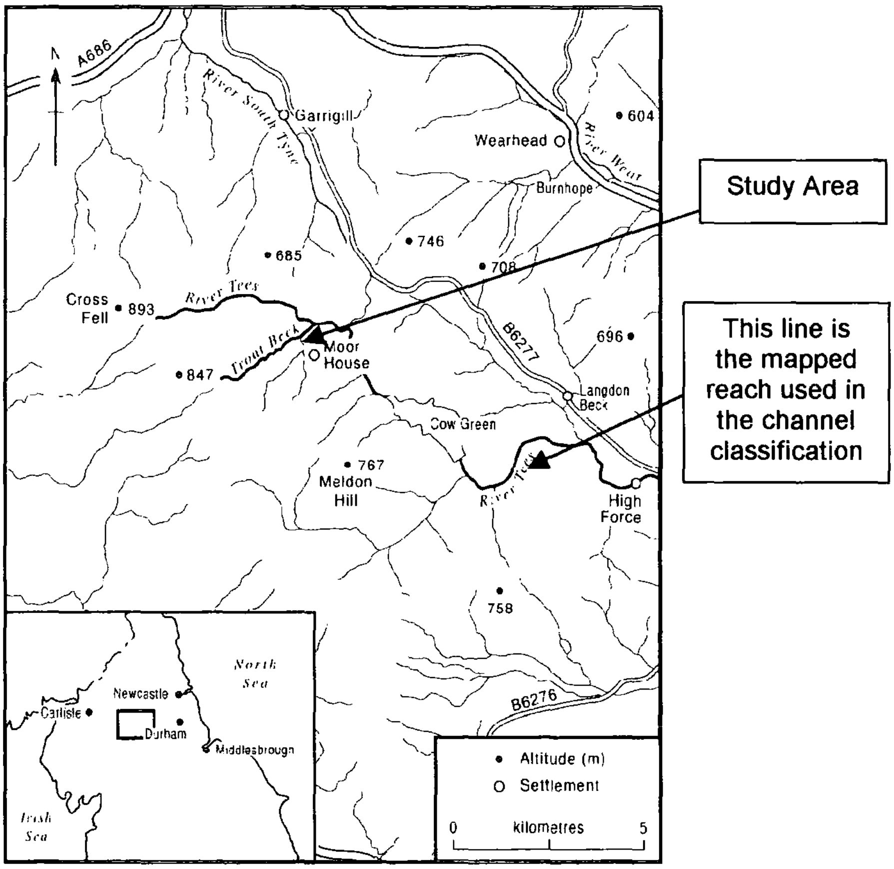
- Use coarse-bed material tracers to estimate the frequency of movement of sediment throughout the reach, characterise movement patterns and relate these observations to local flow.

- To evaluate the significance of bedrock channels in the wider upland fluvial system by developing a classification of bedrock channel types and applying this to the Upper Tees catchment.

1.5 Location of Study Area

Moor House Natural Nature Reserve (MHNNR) is located in Northern Pennines, Northern England. The nature reserve is the source of the River Tees and the Tyne also rises on its boundary. The study reach is located on Trout Beck, a tributary of the Tees which joins the river approximately four kilometres from the source. The Northern Pennines are an area of upland moorland and dales at the northern end of the Pennine chain (Figure, 1.1).

Figure 1.1 Location map showing the location of the study area within Northern England and the Northern Pennines. The heavy black line in the diagram shows the channel length mapped in the bedrock reach classification.



The study site at Trout Beck, consists of an upper bedrock gorge which gradually opens out to a channel with a plane bedrock floor which grades into a fully alluvial channel at the end of the reach. The average channel width of the study reach is 13 m. Figures 1.2-1.4 show the differences in the morphology of bedrock and alluvium sections of the reach. At the beginning of the reach a knickpoint waterfall occurs (Figure 1.2). The waterfall drops approximately three metres into a deep plunge pool. The reach then becomes a gorge (Figure, 1.3) with many small bedrock landforms such as potholes and small steps on the bed. The study reach ends in a flat bedrock section which is heavily jointed with many small erosion landforms where the channel is laterally confined by low unconsolidated banks (Figure, 1.4). The reach then ends abruptly in a change from bedrock to a fully alluvial bed. Almost the entire length of Trout Beck occurs on Tyne Bottom Limestone (Carboniferous).

Figure 1.2 Illustration of the upper section of the study reach.

Figure 1.3 Middle study reach, end of gorge section.

Figure 1.4 End of bedrock section of study reach, many small erosional bedrock features and joint structures are visible.

Table 1.1 The main catchment characteristics of the Upper Tees and Trout Beck.

Name of stream	Catchment area (Km^2)	Catchment Length (Km)	Dominant bed Material	Drainage density (km^2/s)	Altitude range (m)
Trout Beck	11.6	6	Limestone, Sandstone, Shale	3.57	530-848
Upper Tees	13.6	7.5	Sandstone, Limestone	3.15	530-893

Table 1.1 summarizes the catchments which are studied (Figure 1.5). Trout Beck rises to an altitude of 848 m. The catchment is formed by the hills of Dufton Fell (768 m) and Knock fell (794 m) in the south and west by great Dun fell (848 m) (Figure, 1.5). The eastern edge of the catchment runs from the northern slopes of Dufton Fell along the margin of Rough Sike down to the confluence with the Tees at Trout Beck foot (Figure 1.5). The study area was extended a further 28 km downstream of the Trout Beck and the Tees confluence for the purpose of the bedrock classification exercise. Mapping was carried out beyond High Force and Low Force (Figure 1.1).

Figure 1.5 Map of study reach and the Upper Tees and Trout Beck catchments areas.

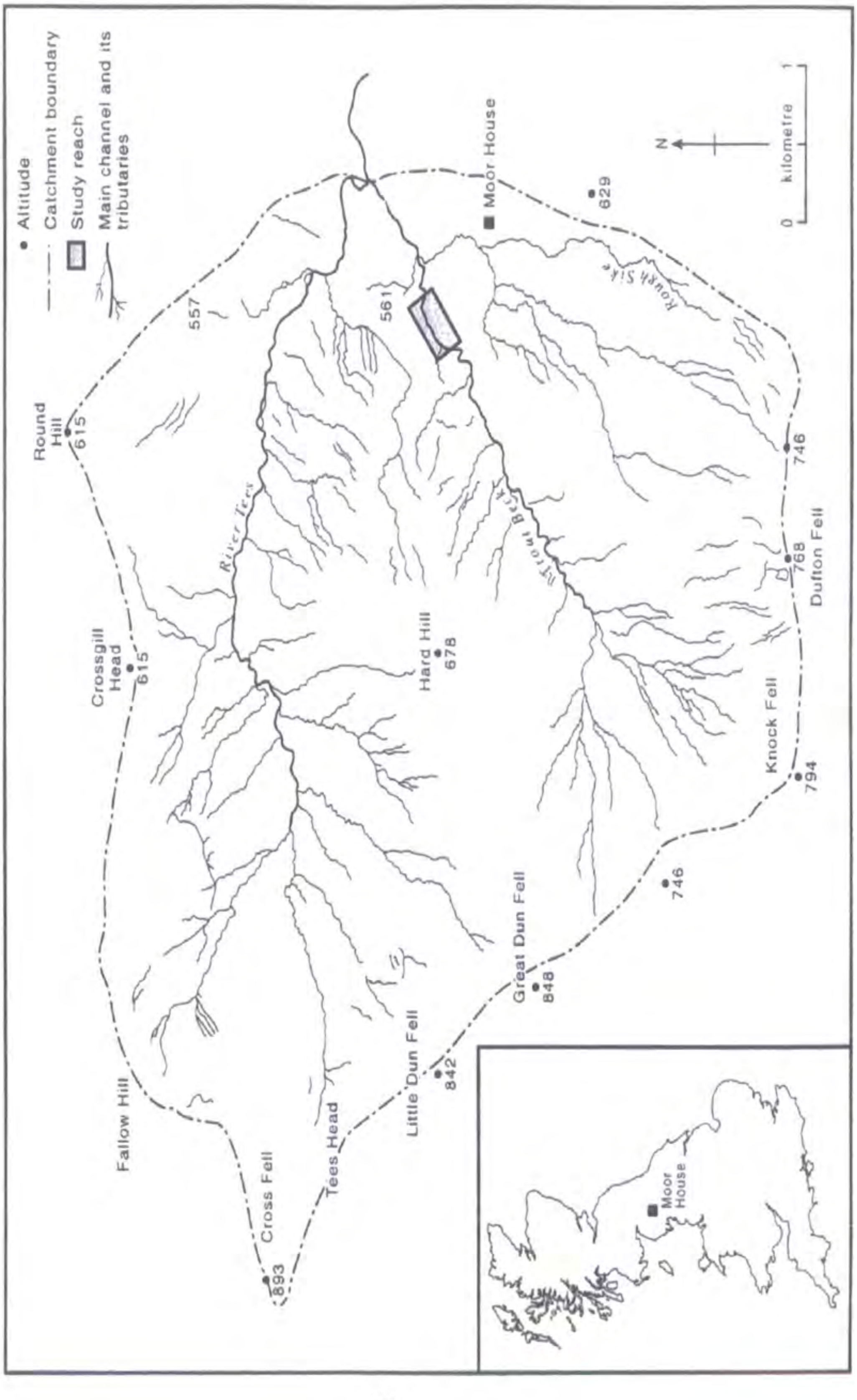


Table 1.2 Table showing stream order and channel distances on both Trout Beck and the Upper Tees

Stream Order	Trout Beck (m)	%	Tees (m)	%	Total (m)
1	180	3.5	240	1	420
2	120	2.5	695	3	815
3	1150	22	1030	5	2180
4	3132	60	7080	34	10212
5	646	12	11943	57	12589

Table 1.2 shows that Trout Beck and the Upper Tees have very different stream order patterns when classified separately. In Trout Beck the majority of the channel, nearly two thirds, has a stream order of four. In the Tees only a third of the channel has a stream order of four. The Tees has a very low percentage of both stream orders two and three. Nearly two thirds of the channel is a stream order of five. This is slightly misleading because Trout Beck is a tributary of the Tees and total channel lengths in the two classifications differ greatly.

1.6 River systems of the area

The main river systems within Northeast England are the Tyne, Wear and Tees, also included are the northern rivers of the Cheviots the Coquet, Aln and Till. All of the rivers flow along an easterly direction towards the North Sea. In comparison with the Tyne, the Tees and the Wear have been studied to a lesser degree. (Macklin, 1997).

The Upper Tees, catchment area (240 km^2) rises on Cross Fell together with the South Tyne. It drains southeast through Cow Green reservoir out into the lowland where it diverts east and meets the sea just south of Hartlepool (Warburton, 1998). These North Pennine rivers share two main characteristics, their flashy nature and the importance of snowmelt in generating runoff (Archer, 1989; 1992).

High runoff is generated by both convective storms and heavy rainfall/rapid snowmelt events, which tend to be responsible for the major floods in the upland region (Newson, 1989).

1.7 Geology and Topography

The North Pennine region has been an area of interest to many geologists in terms of solid geology and structure (Burgess and Wadge, 1974; Dunham, 1990; Taylor *et al.* 1971). The rocks range in age from Ordovician (Borrowdale Volcanics and Skiddaw Slates) to Triassic. The Moor House area is located on the Alston block and is bounded to the north by the Tyne gap and in the south by the Stainmore trough. In the west lies the Pennine fault which produces a large western sloping escarpment. Towards the east the block tilts under the Durham coalfield (Figure 1.6). The vast majority of the area lies above 450 m with the highest point the summit of Cross Fell (893 m). The Tyne catchment is developed predominantly on Carboniferous sandstone, limestone and shale with igneous outcrops occurring at the head of the North Tyne and along the Lower South Tyne valley (Figure 1.7) (Macklin, 1997).

Figure 1.6 Geology of study Area (Source: British Geological Survey Alston – England and Wales Sheet 25 Solid Drift Edition 1973).

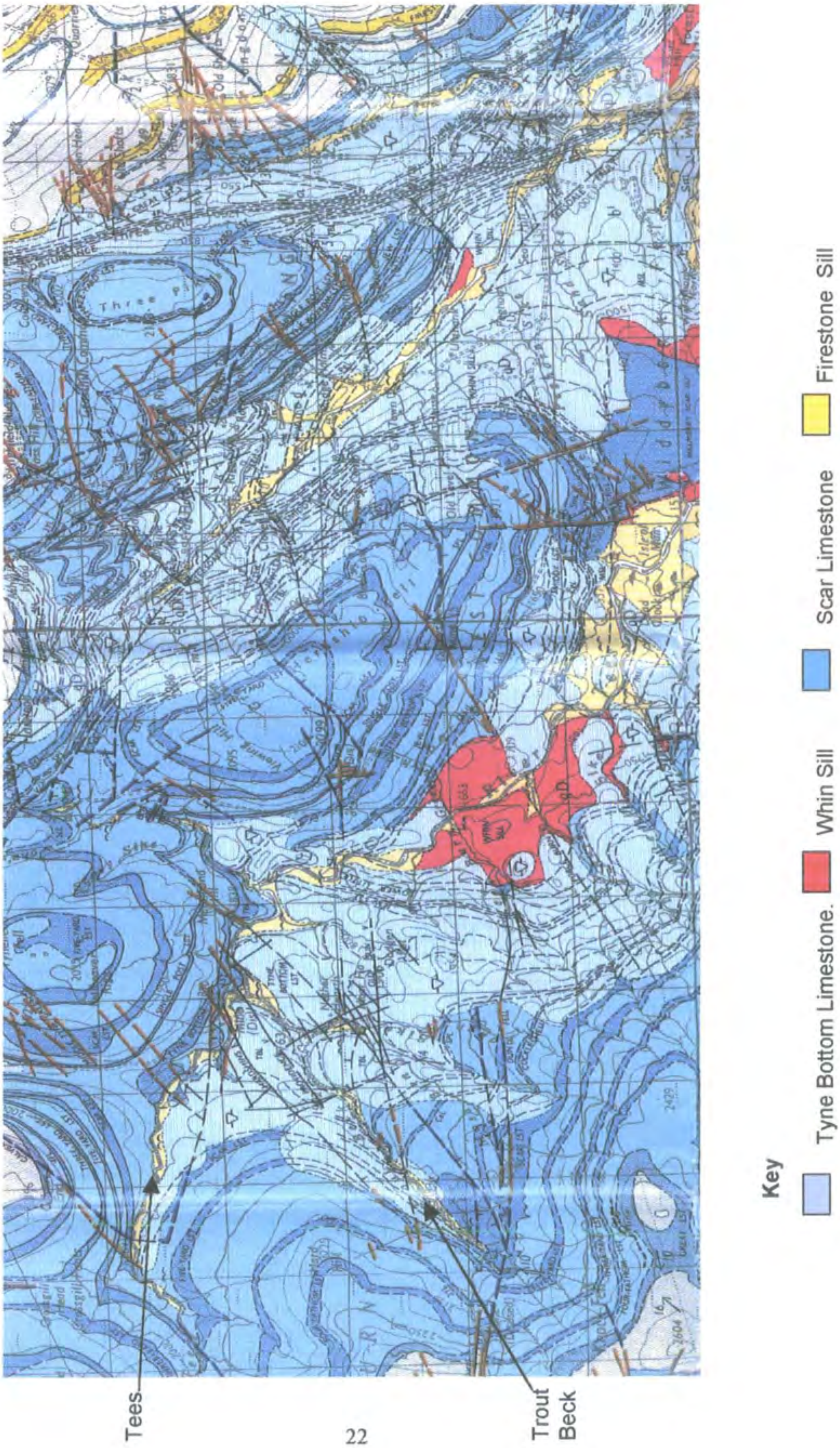
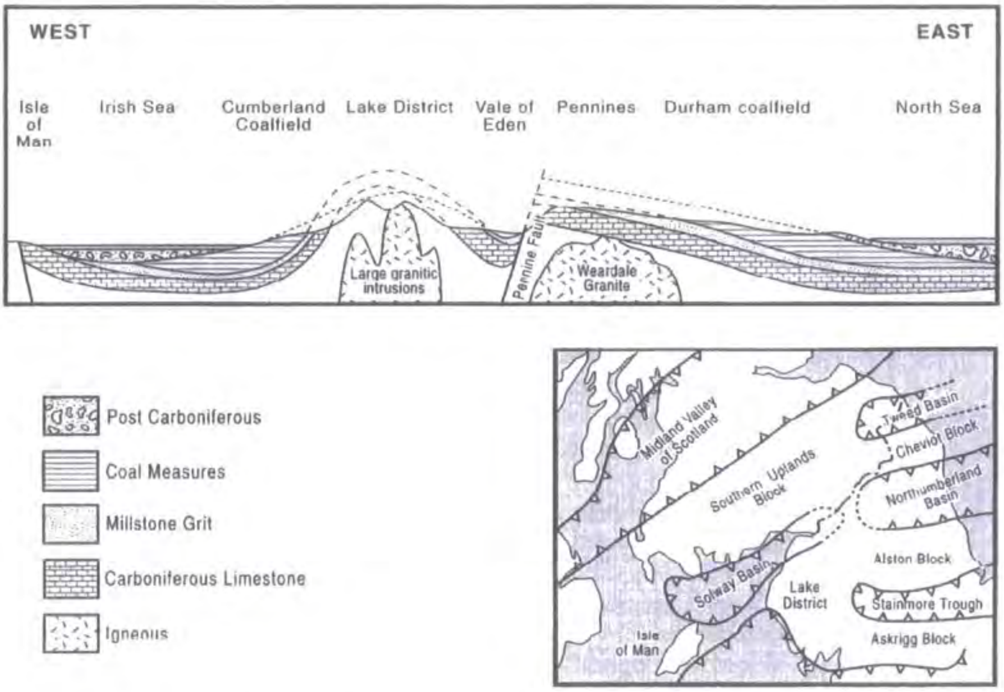


Figure 1.7 Regional geological section and main structural elements of Northern England. (Based on Taylor *et al.* 1971).



The famous dolerites of the Great Whin Sill were introduced during a Permo-Carboniferous episode (296 Ma). During this period crustal movement resulted in the development of the Pennine fault escarpment at the western edge of the Alston block. The eastern dip of the Alston Block which controls the dominant easterly drainage of the regions major river systems. Small localised outcrops of Great Whin Sill exert an important control on many of the river systems. High Force on the River Tees in Upper Teesdale (Figure, 1.8) plunges 22 m over the sill. At this point the Whin Sill is up to 9 m thick and overlies both Carboniferous shale and limestone. Erosion of the shale had resulted in the collapse of the Whin Sill and headward recession of the waterfall (Goudie and Gardner, 1985).

Figure 1.8 High Force Upper Teesdale 22 m drop into a wide bedrock gorge, the waterfall provides a classic example of a knickpoint

The Trout Beck and Tees headwaters are underlain by Carboniferous limestone (Figure 1.7). In the Moor House area there are few natural exposures due to the abundance of deep drift and blanket peat cover. In this region the Tyne Bottom Limestone is almost horizontal and traversed by numerous mineralised minor faults (Figure 1.7). The beds below the limestone are exposed at Trout Beck foot and also at Trout Beck Weir. Low grade metamorphism, in the shales below the Tyne Bottom Limestone at Trout Beck foot may be due to the near proximity of the Whin Sill.

The upland landscape of highly exposed plateaux and open broad ridges, supports a moorland habitat with very few trees. The area contains large areas of blanket bog which have developed on glacial, soliflucted and alluvial materials. The Moor House area is grazed by sheep and the area is an area of outstanding natural beauty and is regarded by many as England's last wilderness (Warburton, 1998).

Soils in the northern Pennines uplands are strongly influence by relief, drainage and parent material. Blanket peat (pH 3.0 to 4.2) is widespread in wet areas (blanket and valley bogs) as are both peaty podzols and peaty gley soils (pH 3.5-4.5). On better-drained areas and slopes, fell-top podzols and brown earths occur (Johnson and Dunham, 1963). Currently the main types of land cover are blanket and valley bogs, (Sphagnum moss), heather and cotton grass moors. On drier slopes, heath, acid grassland and bracken occur and on the high summits sub-alpine grassland. Land use is mainly farming sheep with some beef and also grouse shooting.

1.8 Landscape Evolution

The North Pennine region has widespread evidence of glacial deposition and erosion. Many of the glacial features are in common with features described from the mid Pennine region (Mitchell, 1991). In particular meltwater channels are well developed (Peel, 1949; Beaumont, 1970). During the Late Devensain (18 k BP) a local ice cap developed in the Cross Fell-Wearhead area with ice flowing in an easterly direction along the Wear and the Tees proto-valleys towards the Vale of York and also north along the South Tyne and the Allens (Moore, 1981). The Pennine region also received ice flow from the Lake District and Scotland as the ice flow from the region flowed west to east across the country. The Lake District ice streamed though the Tyne and Stainmore gaps depositing many erratics (Dwerryhouse, 1902; Raistrick, 1931). Erractis from the Lake District have been discovered in the area north of the study reach, as high as 600m (Lunn, 1995).

A complicated flow pattern is thought to have occurred in the North Pennines and it is thought likely that the ice changed positions during the glaciation. During deglaciation, major meltwater channels developed which cut across many watersheds, however deposition from this process was limited (Waters, 1976).

During the Late Glacial and Loch Lomond times the North Pennines did not support an extensive ice cover. However, small local glaciers are thought to have formed for example the escarpment glacier at Cronkley Scar (Mitchell, 1991; Wilson and Clark, 1995), which developed in localities which have a north eastly direction and tend to favour blown snow. The high summits of the Northern Pennines for example Great Dun Fell and Cross Fell feature a range of relict periglacial landforms which are thought to date from this time. Following glaciation the area was influenced by the glacial legacy including reworking of material by the newly developing river systems which were diverted and modified by glacial erosion and deposition. Pounder (1989) suggests that at Cronkley the Tees may have been diverted to a more northerly course by glacial deposits.

By 7000 years ago mixed deciduous and pine woodland became established on all but the most exposed summits and rates of geomorphic change were greatly reduced. During the early and middle Post-Glacial, Mesolithic and Neolithic peoples initiated small-scale clearance of the woodland, first for hunting then for agriculture. Peat started to replaced woodland some 3800 years ago in Upper Teesdale (Pounder, 1989, p18) however in other areas of the uplands this may have started much earlier (Taylor *et al.*, 1971). The pace of woodland clearance continued throughout the Bronze Age and Iron Age and by Roman times the majority of the Pennine uplands would have been cleared of forest (Atherden, 1992). Climate fluctuations and land-use change during the Holocene have led to periods of geomorphic instability (Macklin,1997).

1.9 River Development

More recently mining and degradation of the blanket bog by changing farming and land-use practices have also had a major impact upon the landscape. Mining in particular has had a huge impact on hillslopes, drainage and sediment supply to the river systems (Macklin and Rose, 1986; Macklin, 1997). The South Tyne and tributaries drain the Northern Pennine orefield which was once the most productive lead and zinc mining area in Britain (Dunham, 1990). The effects of mining can still be seen throughout the Northern Pennines today. Post glacial river development has undergone a decline in sediment supply and also isostatic changes. These changes have led to the formation of alluvial terraces (Macklin *et al.* 1992b). Investigations into the mining waste exported through the river system has enabled long term and large scale studies to be produced which show the sediment process and storage patterns of the fluvial system (Macklin *et al.* 1992a; Macklin, 1992).

Deforestation and metal mining have led to changes in the trend of alluviation and in places partial valley infilling (Macklin, 1997). Particularly during the seventeenth and the eighteenth centuries a practice called hushing (hydraulic mining) lead to localised river aggradation and channel planform changes which are particularly notable in the valleys of the Tees and the Wear (Macklin, 1997). The mining waste being phytotoxic due to the high levels of zinc and cadmium caused impaired vegetation growth (Richards *et al.* 1989; Macklin and Smith, 1990), which had geomorphologic implications as bank stability declined which promoted the process of braiding and river instability (Passmore *et al.* 1993; Macklin, 1986).

1.10 Climate

The climate of the Northern Pennine region could be described as cool, cloudy and wet. The climate is representative of the high altitude and the proximity to the sea (Manley, 1942, 1943; Smithson, 1985). The climate therefore is a harsh one, often there are high winds and precipitation on the uplands can exceed 2000 mm. Often the winter snows can lie for up to two months and on bare surfaces frost action is very important (Boardman, 1985; Peitit, 1987). Periodic storms can lead to major changes to the upland fluvial environments. For example the Upper Teesdale and Weardale floods of 1983 caused considerable change to channel sediment systems (Carling, 1986).

Chapter 2 – Literature Review

2.1 Scope of chapter

This chapter discusses channel classification and definitions of bedrock channels, this is considered at a variety of scales including, reach and basin. At the reach scale the landforms of bedrock channels and the influences these landforms have upon the flow of the channel are described. Differences and similarities between bedrock and alluvial channels are discussed. The processes of flow and sediment transport within bedrock channels is outlined. Finally, a brief review of the current and past research undertaken on bedrock channels in the U.K. upland regions is provided.

2.2 Bedrock Channel Classification

At the drainage basin scale channels can be classified in terms of, spatial pattern, (Powell, 1876, 1875, Davis, 1899, Howard, 1987) and hierarchy of stream ordering (Strahler, 1952). Generally stream channels, can be separated into various sedimentary groups including, bedrock, sandy, alluvium or gravelly alluvium (Howard, 1987). There are many different classifications of channel forms, however bedrock channels are most commonly classified at the reach scale (Wohl, 2000).

Bedrock channels can be defined as a channel segment which lacks a coherent bed of active alluvium and is exposed at the land surface (Goudie, 1995, Howard, 1987, Howard *et al.* 1994 and Merritts and Vincent, 1989). Similarly, a bedrock channel has a substantial proportion of the channel boundary (> 50%) made up of exposed bedrock or is covered by an alluvial layer which is largely mobilised during high flows, therefore the underlying bedrock geometry strongly influences both flow hydraulics and sediment movement (Tinkler and Wohl, 1998).

Bedrock channels are most commonly found in rivers in mountainous regions, often as short reaches such as a gorge, cascade or waterfall (Howard, 1998), and they often form headwater tributaries (Carling and Reader, 1982).

Many bedrock channels remain free of bed sediment due to the steep stream-bed gradient found typically in upland mountainous regions (Howard, 1980).Therefore bedrock channels are important because of the impact they have on all aspects of drainage basin geomorphology. During the 1980s there was an observed shift in fluvial geomorphology from research concentrated on sand-bed low gradient channels to gravel-bed, high gradient streams (Hey *et al.* 1982, Beschta *et al.* 1987, Thorne *et al.* 1987, Billi *et al.* 1992). The shift recognized that the coarse-grained, steeper channels differ essentially from channels formed at lower gradient and in finer alluvium with significant differences in sediment transport which influenced the rate and patterns of channel change (Wohl, 2000). Similarly an increase in research in bedrock channels during the 1990s mainly focused in the U.S.A and Australia (Tinkler and Wohl, 1998) has raised important questions about variations in process and form amongst different categories of river channel. There is a lack of current knowledge on bedrock channels in comparison to gravel-bed channels. For example, in the U.K. there has been only one notable study of bedrock hydraulic jumps by Carling (1995). This is despite the widespread occurrence of bedrock throughout much of the U.K. uplands. It is thought that bedrock rivers are more common than generally thought especially in both upland and lowland areas (Montgomery *et al.* 1996). The little research that has been currently undertaken highlights significant differences in many of the hydraulic and geomorphological characteristics of this channel type.

The channel network can be characterised using the depth of alluvium found at different points within the system. The degree of alluviation appears to be key in defining many river channels. Towards the source of a river the upper reaches will encounter bedrock at some point. However as the gradient reduces, the amount of alluvium increases and the channel changes from bedrock-dominated through gravel-bed, to fine-grained alluvium. Using the depth of alluvium present in the channel allows an overall profile of the basin to show the position of different channel types (Rosgen, 1996). As discussed earlier Tinkler and Wohl (1998) used the characteristics of alluvium in bedrock channels to define what actually constitutes a bedrock channel i.e. ≥ 50% of sediment covering the channel width.

Alluvial bedforms and variations in channel geometry have been interpreted as roughness elements that increase the expenditure of the flow energy by generating flow separation and turbulence (Nelson *et al.* 1995). Changes in alluvial channel configuration in response to water and sediment discharge reflect energy availability. Similarly channel geometry in bedrock channels reflects energy availability and competence of flow to erode the channel boundaries.

Bedrock channels offer great resistance to erosion and on a century time scale only small changes to the physical appearance of the channel may be observed. The main control on erosion and the general shaping on the channel is the lithology of the bedrock. The morphology of the channel is an expression of the relationship between the fluvial forces and bedrock resistance (Tinkler and Wohl, 1998). The morphology of the bedrock channels vary depending on the type of geology in the channel. The forces to overcome a quasi-horizontal well-bedded sediment and a "chunky" lithology are different with the later requiring larger shear stresses (Tinkler and Wohl, 1998).

Bedrock channels are important in fluvial geomorphology because it is thought that the rate of bedrock incision may limit the rate at which base level change is transmitted along a drainage basin (Tinkler and Wohl, 1998). Bedrock channels involve changes on a resistant boundary which is usually part of the drainage basin bedrock. Howard (1980, 1998) states that weathering must precede the process of erosion in order that there is sufficient substrate, which is used in the erosion process of abrasion, to be produced. The base level changes effected by erosion have both a local effect and a feedback effect to the rest of the basin. Bedrock channels are important in governing hillslope stability they play an important role in sediment transport and contribute to the flashy nature of upland catchments.

Table 2.1 Examples of research conducted on different types of bedrock landforms (After Wohl, 1998, p135).

Location	**Landform**	**Reference**
California	Terraces	Merritts *et al.* 1994
Canada	Knickpoint	Gilbert, 1895
Texas	Potholes	Blank, 1958
Sweden	Potholes	Angeby, 1951
Spain	Potholes	Lorenc *et al.* 1994
Oregon	Step-pool sequences	Duckson and Duckson, 1995

Table 2.1 demonstrates studies which have been conducted on different bedrock landforms. Of the little research which has been conducted worldwide on bedrock channels the majority has focuses on the unusual landforms produced. The research is heavily concentrated in Canada and the U.S.A. However the process of erosion in bedrock channels in very slow as in glaciers and many of the landforms found in glacial erosion have similarities with those found in bedrock erosion. In

particular pothole formation is an important landform produced by glaciers and also bedrock rivers.

2.3 Significance of the study scale

There are many different scales at which fluvial geomorphology studies can be undertaken. The regional scale includes several drainage basins which are similar in climate, lithology and tectonic regime. Scale is important in bedrock channel studies due to the influence lithology can have on the channel development. Depending on the study site there may be small sections of exposed bedrock or in other cases extensive reaches. Studies at a regional scale often lack the detail acquired from studying a specific reach, however they provide an overall summary of events occurring across a large area (Wohl and Ikeda, 1998). Differing scales of study allow different measurements to be taken and various field techniques to be used. Table 2.2 shows a comparison between the different study scales used in bedrock channel investigations

Table 2.2 Different scales of study used in bedrock channel investigations

Scale	Type of study	Area	Author
Basin	Long profiles	South east Austraila, Macleay River.	Weissel and Seidl, 1998.
	Field Based	California U.S.A.	Merrits *et al.* 1994.
	Computer modelling	U.S.A	Howard *et al.* 1994.
Reach	Fissure erosion	Japan	Toda, 1994.
	Urbanized bedrock erosion	Cooksville Creek, Mississauga, Ontario, U.S.A.	Tinkler and Parish, 1998
	Active Bedrock floored river channels erosion rates and scaling.	Indus River Pakistan	Hancock *et al.* 1998.
Cross-section	Erosional landforms meso-scale	North east Australia.	Wohl *et al.* 1993.

Table 2.2 shows the different scales at which bedrock studies have been undertaken. Basin-scale refers to one single drainage basin, which can vary in size depending on the size of the river which is being studied. Basin research often focuses on evolution of the longitudinal profile at time scales of usually decades (Weissel and Seidl, 1998). Weissel and Seidl (1998) use aerial photographs and river terrace mapping to establish the difference in long profile. Methodologies such as geomorphic mapping and channel surveys (Merrits *et al.* 1994) or computer modelling (Howard *et al.*1994) can also be used on a basin scale to determine patterns of change or erosion through time.

Within a river basin the drainage system can be broken down into reaches. Reach classification is based on hydrology/hydraulics, channel planform, bedforms or a combination of these variables. Reach-scale studies commonly examine a length of channel with consistent substrate and morphology. Studies of this type often concentrate on the process of erosion and deposition and how they affect channel morphology. Research on this scale often has a wide variety of both spatial and temporal scales (Toda, 1994; Tinkler and Parish, 1998). Tinkler and Parish (1998) in a study of recent adjustments to the long profile of Cooksville Creek in Mississauga Ontario show increased bedrock erosion rates due to weak shale and limestone together with increased urbanisation.

The cross section scale refers to a particular section of channel at a specific point along the long profile (Wohl, 2000). This allows the detailed morphology of a small section of the river to be studied. Cross section studies are usually undertaken over varying distances but usually nested within a reach. The studies are often compiled using many cross sections at set intervals down a reach (Wohl, 2000).

The cross sections can be used as a method to observe sedimentation changes to the bed and also location and size of eroisonal landforms.

2.4 Channel Morphology

The gradient of a bedrock channel is usually steeper than alluvial channels, even though locally it may appear that large sections of bedrock rivers are low angle flowing along horizontal bedding planes (Miller, 1991a). The increase in gradient due to an increase in flow leads to an integration of step-pool sequences which gradually become drowned out (Tinkler and Wohl, 1998). Morphological change in the channel is uni-directional, rock that is removed from the bed of the channel lowers the local base level for all points upstream. This permanently changes the local velocity in the channel as the bedrock is not replaced. This is in contrast with the processes which operate in fine-grained alluvial and gravel-bed rivers (Tinkler and Wohl, 1998). The large variation of sediment size in bedrock channels reflects the controls upon the channel this may be due to the geology or lithology of the bed structure or hydraulic changes which may be a function of varying degrees of the channel substrate and flow (Miller, 1991b). Kiefer (1988, 1989) states the importance of tributaries and the potential impacts they can have on bedrock channel systems due to the sediment and flow changes they may cause. Variability in flow and sediment supply has important implications when a tributary joins the main river. Figure 2.1 shows how landforms within a bedrock system relate with each other.

2.5 Landforms of bedrock erosion.

Erosion processes dominate the morphology of a bedrock channel. Erosion operates usually on small spatial scales between millimetres to metres as a function of both the chemical and physical mechanisms causing erosion.

Figure 2.1 shows many landforms which are commonly found within bedrock channels. Often a bedrock section contains a knickpoint, a weakness in the rock which is commonly seen as a waterfall. An example of this within the U.K. context, is Aysgarth Falls in North Yorkshire. The waterfall often leads into a gorge section, this varies in depth but steep bedrock banks are often present e.g. High Force, Upper Teesdale .

Figure 2.1 show the differences in the range of scales of landforms which can be produced by bedrock erosion. Table 2.3 shows differences in the scale of bedrock forms from macro landforms such as waterfalls and gorges to potholes which are meso erosional landforms. The table also illustrates bed characteristics that may enhance erosion.

Figure 2.1 The bedrock channel system (Warbuton unpublished, 2003).

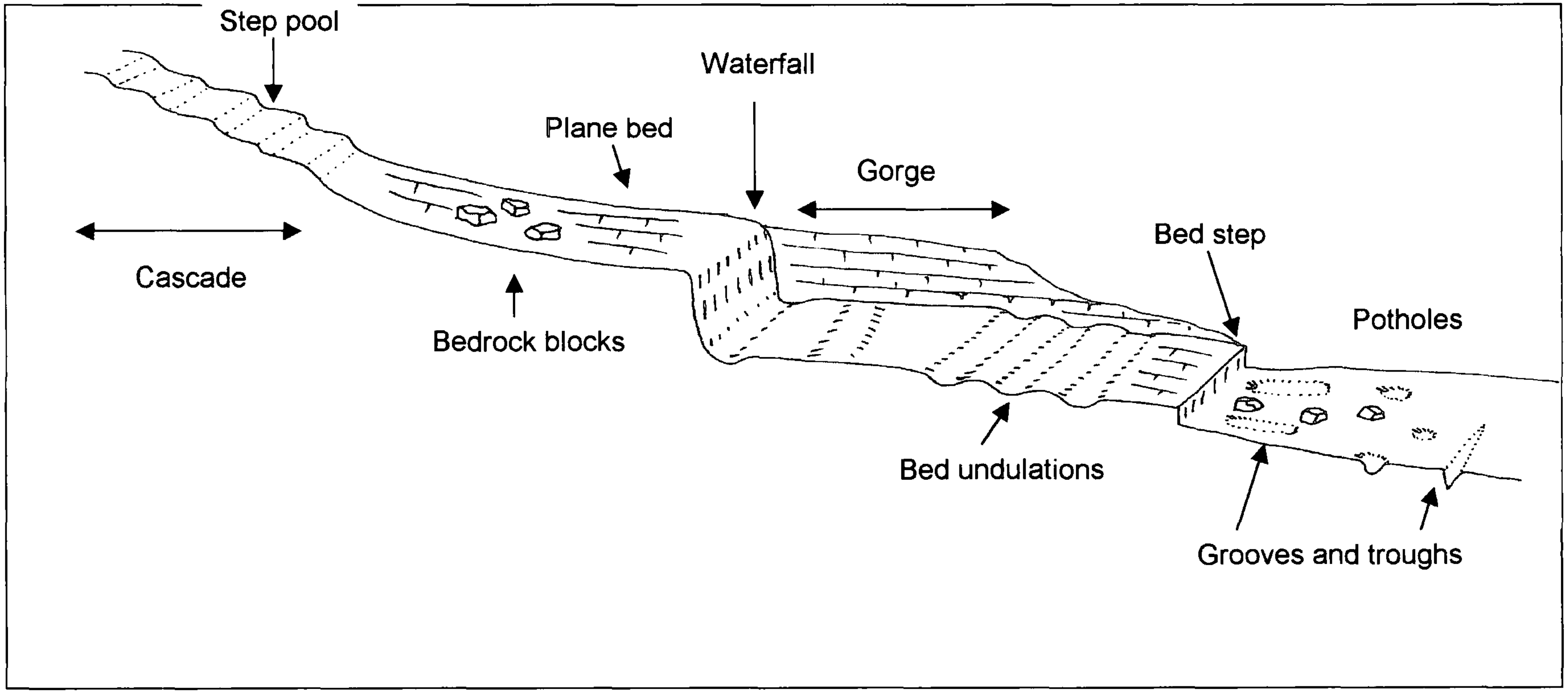


Table 2.3 Table showing different scale landforms (Wohl, 1998, p134).

Scale	Erosional Characteristics
Micro-scale (mm to cm)	Abrasion, flaking or plucking of individual grains or small pieces of rock
Meso-scale (cm to m)	Selective erosion of portions of the channel boundaries across a cross-section or along a reach: produces potholes, longitudinal grooves, knickpoints, undulating walls, inner channel, pool-riffle or step-pool sequences.
Macro-scale (m-km)	Reach- to basin-scale channel morphologies in planform (meandering, downstream alterations in width and gradient), and in gradient.

2.5.1 Knickpoints

A knickpoint is a step-like discontinuity in the longitudinal profile of a river channel. A waterfall frequently occurs at these points due to the sudden change in height of the channel bed and in this respect a waterfall can be defined as a stream of water which falls from a height. This process involves high amounts of energy dissipation and often occurs at sites where a softer rock is eroded beneath a harder rock (Goudie, 1995). The knickpoint may also form as a result of an increase in the ratio of water and sediment discharge (Miller, 1991b). They often occur singularly or in small groups and erode headward over time. This is in contrast to the stationary bed steps (Wohl, 2000). They may occur in alluvium which is unconsolidated however they are best formed in bedrock. Many of the world's greatest waterfalls show the vertical drop which is associated with a knickpoint (Montgomery and Buffington, 1997). A knickpoint is created when a base level fall occurs or uplift of the drainage basin (e.g. isostatic change following glaciation). Uplift leads to an increase in channel gradient and thus the ability of the river to incise is greater and a knickpoint originating at the channel mouth erodes upstream (Wohl, 2000).

Figure 2.2 shows a knickpoint waterfall on Trout Beck which occurs just above the confluence with the Tees, Upper Teesdale , U.K.

Figure 2.2 Knickpoint just above the Weir on Trout Beck (Upstream, NY75749, 33471)

2.5.2 Gorges

Gorges are landforms which are often formed from knickpoint erosion. Headward retreat of a knickpoint through a resistant bedrock unit may leave behind a deep narrow canyon with walls that are only marginally changed by slope processes (Wohl, 2000). The steep face of the knickpoint may be maintained during the headward erosion. Weaker rock underneath can be eroded at a higher rate resulting in the more resistant rocks forming an overhanging outcrop which eventually breaks under the strain and the process begins again (Wohl *et al.* 1994). A good example of this is High Force on the River Tees. Over many centuries the river has slowly incised back into the bedrock leaving a gorge which is 1 km long.

Through this procedure which is initiated through a waterfall the gorge has been slowly carved out through time (Figure 2.3).

2.5.3 Cascade

Cascades are characterized by tumbling flow, however reaches often exert very different flows and discharges (Bisson *et al.* 1982, Grant *et al.* 1990). Generally cascades occur on steep slopes which are narrowly confined by the valley walls and often have disorganised bed material. These characteristics are common to bedrock channels which occur in mountainous regions. They display tumbling flow over individual grain-steps and turbulence associated with jet and wake flow around grains dissipates much of the flow energy (Montgomery and Buffington, 1997). Results of a tracer study by Kondolf *et al.* (1991) showed there are two possible thresholds for sediment transport in cascade channels. Firstly moderate recurrence interval flows; bedload material is rapidly and efficiently transported over the more stable bed. In bedrock river channels sediment movement in particular bedload movement is high under peak discharge conditions. The second movement is under extremely high flow conditions which have a recurrence interval of at least one or more years. However a lack of significant channel storage and rapid scour of depositional sites during high flows suggest that sediment transport is efficiently limited in cascade channels.

2.5.4 Step-pool channels

Step-pool channels are characterised by longitudinal steps formed by large wooded debris or large clasts organised into accumulations spanning separate plunge pools which contain finer materials (Griffiths, 1980, Whittaker and Davies, 1982, Whittaker, 1987a, 1987b, Chin, 1989). Step-pool sequences are found in a variety of different upland environments from cold temperate (Grant *et al.* 1990) to hyperarid (Wohl and Grodeck, 1994). Variations in step spacings have been found from 10's of metres (Abrahmans *et al.* 1995) to 100's m (Bowman, 1977). Within bedrock river channels step-pool sequences are found on the bedrock bed. These landforms cause changes in flow dynamics due to local gradient changes. The steps within the river may be steep in gradient and the pools deep. Figure 2.5 illustrates a step-pool sequence on the river Caldew in Cumbria, Northern England. Montgomery and Buffington, (1997) suggest that primary flow and channel bed fluctuations in step-pool reaches are vertical rather than lateral. Step-pool channels show a pool spacing of roughly one to four channel widths (Chin, 1989, Grant *et al.* 1990). Which is significantly less than the five to seven channels widths that typify self formed pool-riffle channels (Leopold *et al.*1964) suggesting initial control by a large-scale turbulent eddy scaled to the channel size (Keller and Melhorn, 1978). Wohl *et al.* (1993) point out the important of gradient in the formation of pools. Other important variables in the formation of the pool-riffle sequence are boundary resistance/bedrock (Roy and Abrahams, 1980) and also debris and obstructions (Lisle, 1986, Montgomery *et al.* 1995). Steps provide large elevation drops and greatly increase roughness (Ashida *et al*, 1976). Montgomery and Buffington (1997) noted that step-pool sequences are most commonly occurring at reach gradients of 0.03 to 0.10 (Figure 2.5). Figure 2.3 shows the part of the study reach in the bedrock gorge section. Within this section many small step-pool sequences occur along the bedrock bed. However there are also a few larger steps, these cause a steep gradient change and often led to deep pool development. The bedrock section between the step pool sequences are often low in gradient.

2.5.5 Plane-bed Channels

Often found in upland mountainous environments (Wohl, 2000), they lack the well-defined occurrence of bedforms that characterise both step-pool and pool-riffle channel sequences (Montgomery and Buffington ,1997). Plane-bed channels are most common at channel gradients of 0.01 to 0.03 they can be covered by a surface layer of coarse clasts formed on bedrock (Wohl, 2000). Buffington (1995) also suggests that the bed may be heavily armoured above the bedrock layer. A significant difference between alluvial and bedrock channels is that of gradient. Bedrock channels are found in high, upland areas which nearly always have a steep gradient (Wohl and Merritts 2001). Alluvium channels however are most commonly found on the floodplains which occur at low gradients 0.03 Australia (Lane *et al.* 1995). The gradient is fundamental as it affects both the flow and in turn this affects the transport of sediment. Figure 2.4 illustrates an example of a plane bed channel in the Upper South Tyne, UK.

Although research into plane-bed channels indicate that sediment supply is limited during most discharges, there is however a correlation between bedload transport rate and discharge during the higher flows that mobilise the bed (Jackson and Beschta, 1995 Sidle, 1988). However studies have indicated that during high discharges these channels are transport limited (Wohl, 2000). It would appear that sediment movement appears to be higher during high flows, however whether there is a maximum threshold of sediment movement within such channels is debateable. Carling *et al.* (2002) has developed an equation which uses flume data to predict movement of blocks under critical flow conditions. This is particularly important in bedrock studies in establishing the effects of friction and drag and also how different block forms move.

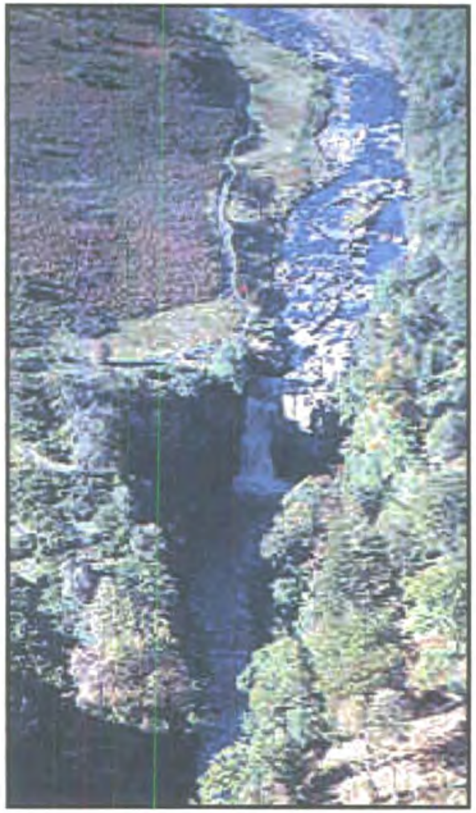


Figure 2.3 High Force Aerial view

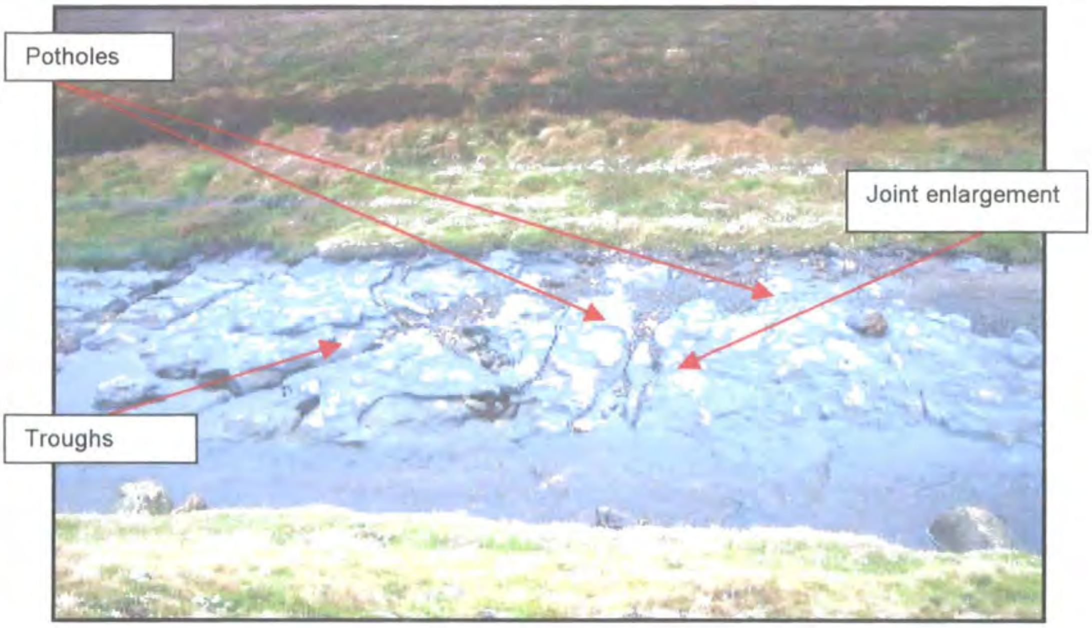
Figure 2.4 South Tyne bedrock plane bed sequence

Figure 2.5 Caldrew step-pool sequence

2.5.6 Small scale landforms

Bedrock channels with a uniform bed gradient at the reach scale may also have differential erosion across the channel. These areas of enhanced erosion may consist of longitudinal or transverse scoops, troughs, potholes or inner channels (Figure 2.6). Along with waterfalls these aspects of bedrock channel erosion were one of the first to be studied in detail (e.g. Ives 1948 and Gregory 1950). Irregularities in alluvial channel beds may be swiftly modified as turbulent flows and shear forces reshape the bed. However in bedrock channels greater turbulence, lower sediment supply and a higher boundary resistance may lead to the enhancement of erosional features.

Figure 2.6 Small scale bedrock features in Trout Beck within the study reach.



2.6 Erosional Landform Production

The mechanisms of landform production in bedrock channels remain poorly understood. It is thought in extreme flows cavitation was cited as an important process under conditions of turbulent flow (Baker, 1973). However there is no real event based measurements to substantiate such a theory and this remains one of the hardest areas to investigate in the study of bedrock channels. Chapell's (1974) work on carbonate terrains in Papua New Guinea tried to estimate the relative proportions of channel erosion by different erosional processes. Chapell estimated erosion in coral reef terraces of varying age by using cores and radiocarbon dating. He noted that different rock types erode at different rates and also different hydraulic conditions cause different erosion rates in the channel system. He proposed a best fit solution which combined results from four valleys. However this is specific to the coral reef and is difficult to apply more generally due to the differences in hydraulic conditions and bedrock composition.

2.7 Flow Dynamics and Hydraulics

The balance of process and form in channels varies spatially and temporally. Both process and form in bedrock channels operate over longer timescales than those witnessed in alluvial channels. The most important control on flow is gradient. Howard and Kerby (1983) show that bedrock channels are steeper than any other fluvial channels. Flow in bedrock channels at low stage show greater velocities and shear stress than those in alluvial reaches and unusually possess highly aerated and turbulent flows (Tinkler and Wohl, 1998).

Critical flow velocity is described as the velocity which is just able to entrain the bed material (Carling and Tinkler, 1998). Critical flow velocity is different from that in alluvial channels because of smooth boundary conditions (Tinkler and Wohl, 1998).

Critical flow velocity is dependent on roughness, slope and channel width, attempts to find a consistent relationship for conventional hydraulic geometry as in alluvial channels have been largely unsuccessful (Tinkler and Wohl, 1998). Critical flows in bedrock channels tend to be confined to a restricted spatial zone.

Depth is an important variable to consider, as depth increases in bedrock channels the flow may remain critical or even become supercritical over a cascade or revert to sub critical in a smooth section. Flow may gradually become critical, as flow down steps and smaller knickpoints begin to disappear if the depth remains constant as discharge increases (Tinkler and Wohl, 1998). Field evidence (Tinkler, 1997a, b) suggests that flow may remain critical with increasing stage. Alternatively velocities may subside without increasing depending on the intensity of the rainfall and the increase in the flow, as energy is dissipated across the entire channel width. The theory of supercritical flow is controversial. It is generally only found in high magnitude events. It is though that during supercritical flow in bedrock channels sediment transport rates may be limited. High roll waves which surge down the channel are associated with supercritical flow. Hjalmarson and Phillips (1997) use eyewitness accounts to construct their theory of supercritical flow (Tinkler and Wohl, 1998). There is little evidence of detailed measurements taken during large-scale flood events. It is because of the inability to collect data during a large bedrock flood event. Due to the size of the material transported which can cause damage and loss of equipment.

Flow resistance occurs when the pressure drags on grains on the bed surface and on bed undulations (Griffths, 1987). As the depth increases individual particles influence a lower proportion of the flow and the effect of grain resistance is reduced. However poorly sorted clasts and shallow flow which often occur in bedrock rivers tend to make grain resistance more important than in most low gradient rivers (Wohl, 2000). The flow velocities associated with shear stress and lift forces are strongly related to flow resistance because the velocity distribution is also affected by bed material size distribution and channel gradient.

Flow separation occurs when flow along a physical boundary develops an adverse pressure gradient (a reduction in the upper profile). This is more commonly found at high Reynolds numbers (Tritton, 1998). Kirkbride (1993) used flume experiments to observe the influence of bed roughness on turbulence. Flow separation often occurs when an obstacle is in place which alters the flow in the channel. Flow disruption around an obstacle, depends on the height of the block. The flow behind the block slows due to the resistance of the block and the increase in velocity as the water builds up behind the block. The flow is accelerated either side of the block at an increased rate. The flow accelerates faster around the block than the flow behind the block even though there is friction with the bed, block and walls of the flume. The obstacle causes huge changes in velocity directly in front of the block, due to the build up of water behind the obstacle. The flow accelerates over the block due to the force of gravity causing a scouring effect as it hits the bed (Webber, 1965).

A step in the bed profile produces an increase in velocity due to the acceleration over the step in the bed due to gravity. An air pocket is produced directly in front of the step which may cause a vacuum if the air is not replenished causing water to be drawn back towards the step. The step produces local high velocity flow which exerts great force on the bed and also any sediment (Webber, 1965).

2.8 Sediment Transport

The velocity and turbulence conditions in rock-bed rivers are not well documented. It has been stated that macroturbulence is responsible for suspension of substational blocks and cobbles (Matthes, 1947). Putzer (1971) suggests that macroturbulence is a factor in formation of lateral potholes. The critical shear stress for sediment movement will be a function of local hydraulics, as well as grain size, shape, sorting and packing (Barta *et al.* 1994, Barthink and Michalik, 1994, Moore and Diplas, 1994).

Sediment load between alluvial and bedrock channels varies both in magnitude and content. Bedrock channels have a higher proportion of bedload in the sediment discharge whilst alluvium channels have high concentrations of suspended load (Kelsey, 1996). There are also notable differences in the rate and potential for bank erodability, due to the time it takes to erode bedrock (Schumm, 1966) when compared to similar erosion rates in alluvium.

Bedrock river channels are often characterized by coarse sediment in diameter from a sand size upwards which often includes boulders of one metre or more. Very little fine sediment is found within bedrock channels. Boulders usually remain stationary for many years in the channel, however in a large floods (e.g. with an occurrence interval of approximately fifty years) the velocity may be high enough to move such large boulders. However there is also evidence that boulders of large sizes are able to move in floods which occur during a normal range (Tinkler and Wohl, 1998). It would appear that there is some disagreement under what conditions boulders move Researchers have traditionally assumed they move under high flow conditions, Tinkler and Wohl (1998) suggest that they move under normal flows as well.

In bedrock rivers suspended sediment plays just an important role as in the fluvial geomorphology of alluvial rivers. Although sediment moves as bedload more than 25% of the sediment which is moving in many rivers is suspended (Williams and Rosgen, 1989). Studies of high-gradient rivers have indicated that bedload composes a larger proportion of the total sediment yield along channels which have a higher gradient when compared to those at a lower gradient (Mosley, 1978; Harvey, 1980). It has been assumed that rocky rivers carry no other sediment apart from suspended sediment at low flow however this depends on the nature of sediment available to the catchment (Wohl and Merritts, 2001). For example on the Niagara peninsula up to 0.5 cm of fine silt is deposited on the bedrock as the stage decreases; however this is washed away during intense rainfall and rising stage (Tinkler and Wohl, 1998) (Figure 2.7). The flux of suspended sediment is closely linked with discharge and at low stage little suspended sediment is carried in bedrock rivers. Leopold (1992) states that bedload is also more important generally than suspended load in forming and changing the channel of a mountain river.

Figure 2.7 Build up of fine sediment on the bedrock plane of the Trout Beck study reach.

During the 1980s research on gravel-bed rivers led to attention on bedload entrainment and transport from poorly-sorted channel beds. Attempts to quantify entrainment involved specifying critical shear stress, packing, pivoting angle and grain diameter. These approaches largely ignore the implications of lift force and describe conditions which may be deviated from mean shear stress. Therefore this approach has largely been replaced by physical based stochastic models which focus on velocity fluctuations and variations in grain size using the pivoting angle (Richards, 1990).

Bedload transport studies demonstrate that steep channels in mountain drainage basins are typically supply limited receiving seasonal sediment inputs (Nanson, 1974, Griffiths, 1980 and Whittitaker, 1987a). Bedload transport along steep gravel-bed rivers is extremely hard to measure directly (Ryan and Troenale, 1997). Depositional characteristics of sand and gravel have been used to estimate discharge and hydraulic variables along bedrock canyons (Wohl, 1992). Bedload movement may also be established from a subset of marked tracer particles that are assumed to represent a proportion of the total movement. Numerous studies of bedload measurement have demonstrated that bedload movement occurs episodically along a given channel reach (Hoey, 1992).

Bedload transport rates and the distance bedload is transported vary widely among mountain rivers as a function of channel morphology, grain size distribution, magnitude and frequency of discharge and other factors. There are complex interactions between hydraulics, sedimentology and grain characteristics.

2.9 Flume Studies

There are now a variety of experiments in the laboratory using flumes which establish the critical flow and velocity conditions for the transport of bedrock blocks. Carling *et al.* (2002) have conducted experiments in the flume which focus on the initial movement on bedrock blocks. As mentioned previously the equation developed by Carling *et al.* can be used to predict movement of blocks placed on the bed of the channel during critical flow conditions. The research conducted in the flume focuses in particular on the movement of large boulders on smooth surfaces such as bedrock. Carling *et al.* (2002) conducted experiments looking at the motion of single blocks and then multiple block groups. In the flume it is demonstrated the submergence or emergence of the blocks is critical and can affect the drag efficient. Equation 2.1 aims to predict the critical velocity at which the block will move. The equation was developed under experimental conditions in the flume but can be transferred to river channel. The critical velocity (U_c) is given by:

$$U_c^2 = \frac{2(\rho_s - \rho)\, g\, D_b}{\rho} \qquad \frac{\mu_f}{C_d + [C_l\, \mu f\, (D_b / D_c)]} \qquad \text{(Equation 2.1)}$$

$(\rho_s\text{-}\rho)g$ Immersed mass of boulder with medium and short axes, D_b and Dc. C_l lift

coefficient, C_d drag coefficient , uf friction coefficient. p density of water.

Where $(\rho_s\text{-}\rho)$ is the immersed mass of boulder with medium and short axes, D_b and D_c, C_l is the lift coefficient, C_d the drag coefficient , μ_f the friction coefficient, ρ density of water, g is acceleration due to gravity.

The aim of the equation is to predict the critical velocity at which a block will move based on the size and weight of the block. However fundamentally three coefficients need to be calculated in order to use the equation, they are drag, friction and lift. These can be established using a variety of different methods depending on the type of block used.

2.10 Research in the UK uplands

An increase in research in bedrock channels during the 1990s mainly focused in U.S.A and Australia (Tinkler and Wohl, 1998) has raised important questions about variations in process and form amongst different categories of river channel. There is a lack of research on bedrock channels in comparison to gravel-bed channels and this is reflected in the lack of research on bedrock channels in the U.K. Given the abundance of bedrock river systems in the U.K. uplands this lack of research is surprising. There is however some reference to U.K. bedrock channels in the literature. For example Ferguson (1981) in a survey of British rivers refers to the short sections of rock walled channels which occur for a brief time often at knickpoints such as High Force (Tees), and Aysgarth Falls (Ure), especially in settings where modern rivers occupy previous glacial meltwater channels. The only substantive study on bedrock channels in the U.K. is by Carling (1995) on flow separation berms downstream of hydraulic jumps on Birk Beck a tributary of the River Lune in Cumbria. He found that cobbles and pebbles were swept through jumps and they were deposited in the tranquil flow immediately downstream of the shock waves. In bedrock rivers the sediment is often deposited in the tranquil pools were the velocity is reduced due to the increase in depth. He also suggested that the deposits have significance in reconstructing flood history because the presence of berms determines the former locations of hydraulic jumps and therefore the previous flow structure of the bedrock channel.

Research on bedrock channels in the U.K. is increasing. There is now a bedrock channel discussion forum based at Southampton University. The web site allows for the interaction between international researchers and questions about varying aspects of bedrock channel research may be posted. So far within the U.K. there has been little research conducted on bedrock channels and virtually nothing on re-sedimentation of bedrock channels after a large flood. Little is known about the extent of bedrock channels in upland environments as there have been few attempt to classify upland fluvial systems with respect to the proportion of bedrock channel types. It is therefore hard to state the importance of bedrock channels within the fluvial context when the actual extent of the channels is largely unknown. Furthermore the dynamics of large flood events in bedrock channels are not well documented. However during a large flood event much of the sediment in a bedrock channel is removed and over time replaced. This research aims to provide a classification system for the channel bed and banks to discover the proportion of bedrock channels which exist in the upland environment and to map the movement of sediment through the bedrock reach following a major flood event.

Chapter 3 – Field and Laboratory Methods

3.1 Introduction

This chapter explains the different techniques used in the project. The majority of measurements undertaken for the research are conducted within the 300 m study reach (Figure 3.1). Additional data for the bedrock classification and bed step survey were collected in the wider catchment. The methods used in this research are commonly used techniques which can also be applied to alluvial channels as well as bedrock systems. Figure 3.1 illustrates how the individual methods are linked in the overall research structure. The overall aim of the methodology is to characterise sedimentation changes in the bedrock channel. Figure 3.2 illustrates the sampling and survey times executed during the course of the research.

3.2 Geomorphic Mapping

Geomorphic mapping provides a two dimensional record of channel characteristics. Repeated mapping allows for an accurate picture of channel change to be established over time. This is a technique is often used particularly with aerial photographs, e.g. Tinkler and Wohl (1998) use this techniques to establish sediment levels and change in a bedrock river in Ontario, U.S.A.

Geomorphic mapping was based on aerial photographs taken in 1995. These photographs show the structure of the basic bedrock channel. The channel was mapped at a scale of 1:400. Each of the 30 monumented cross-sections were marked on the map to provide a detailed reference frame for mapping (Figure, 3.3). The points of fixed photography were also noted on a map for reference (Figure, 3.3). Within the channel positions of large boulders and pockets of sediment were mapped. The mapping was completed on six occasions on the 20/11/02, 18/12/02, 13/02/03, 2/04/03, 28/05/03 and 3/07/03.

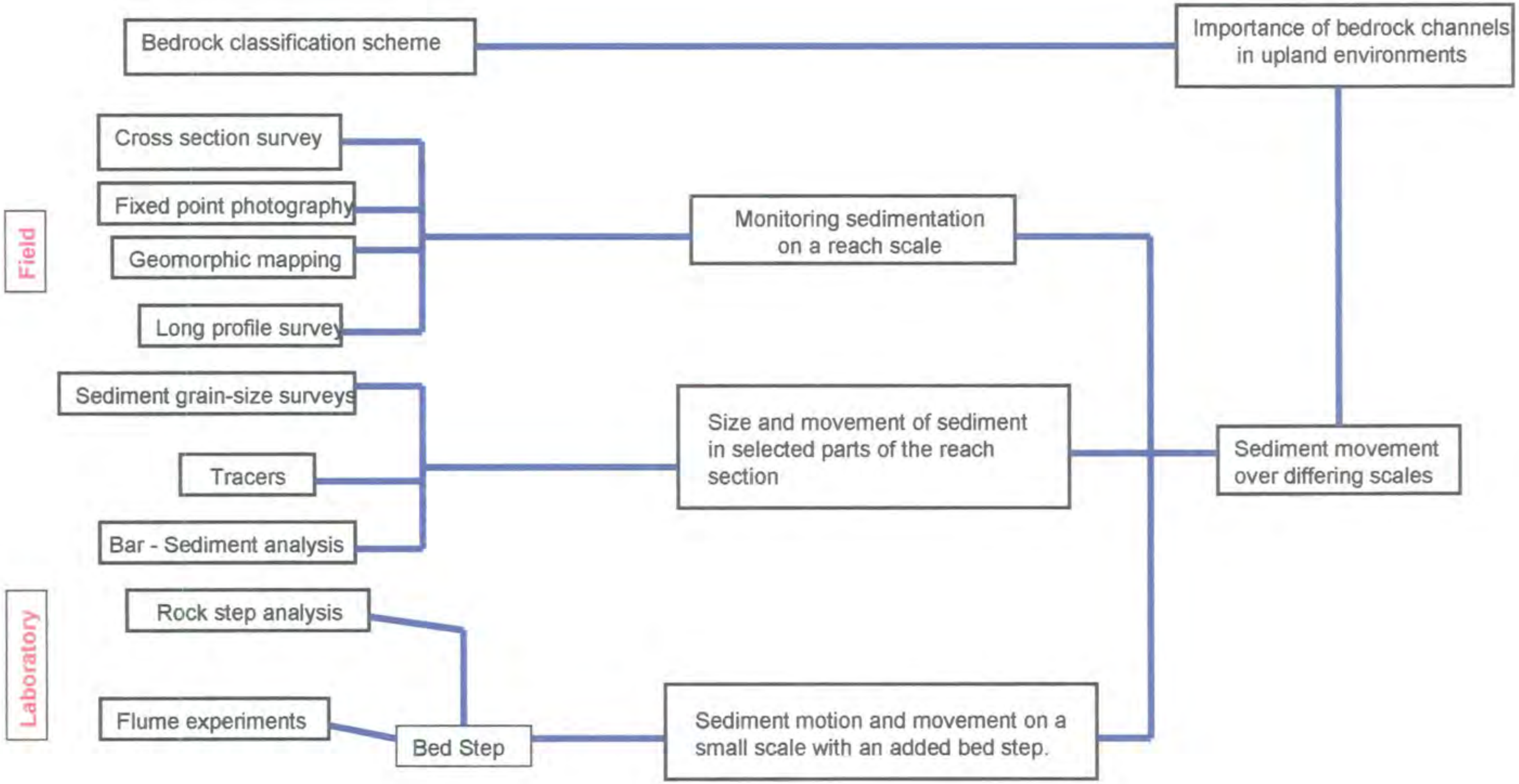


Figure 3.1 Integration of the methodologies used in the research

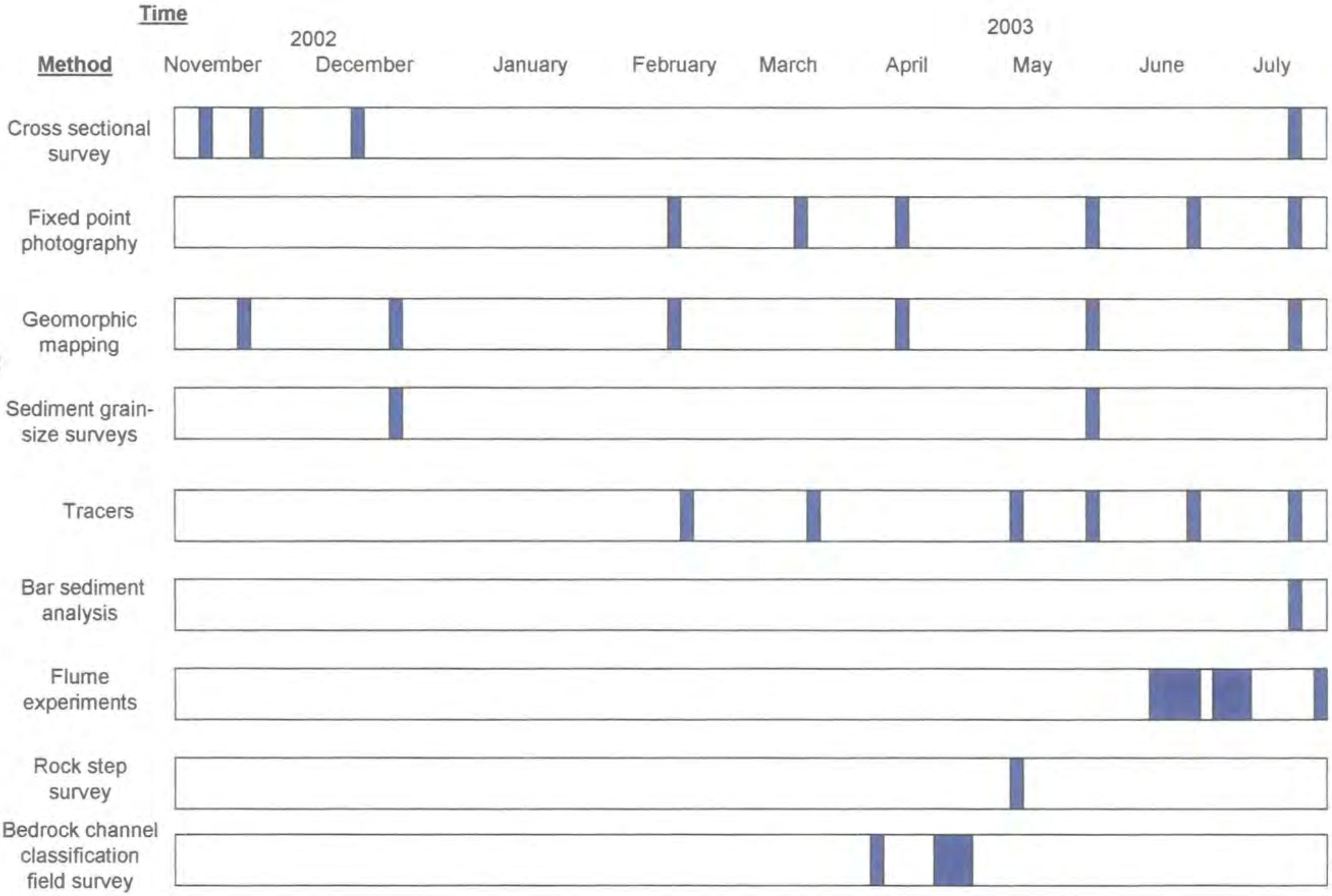
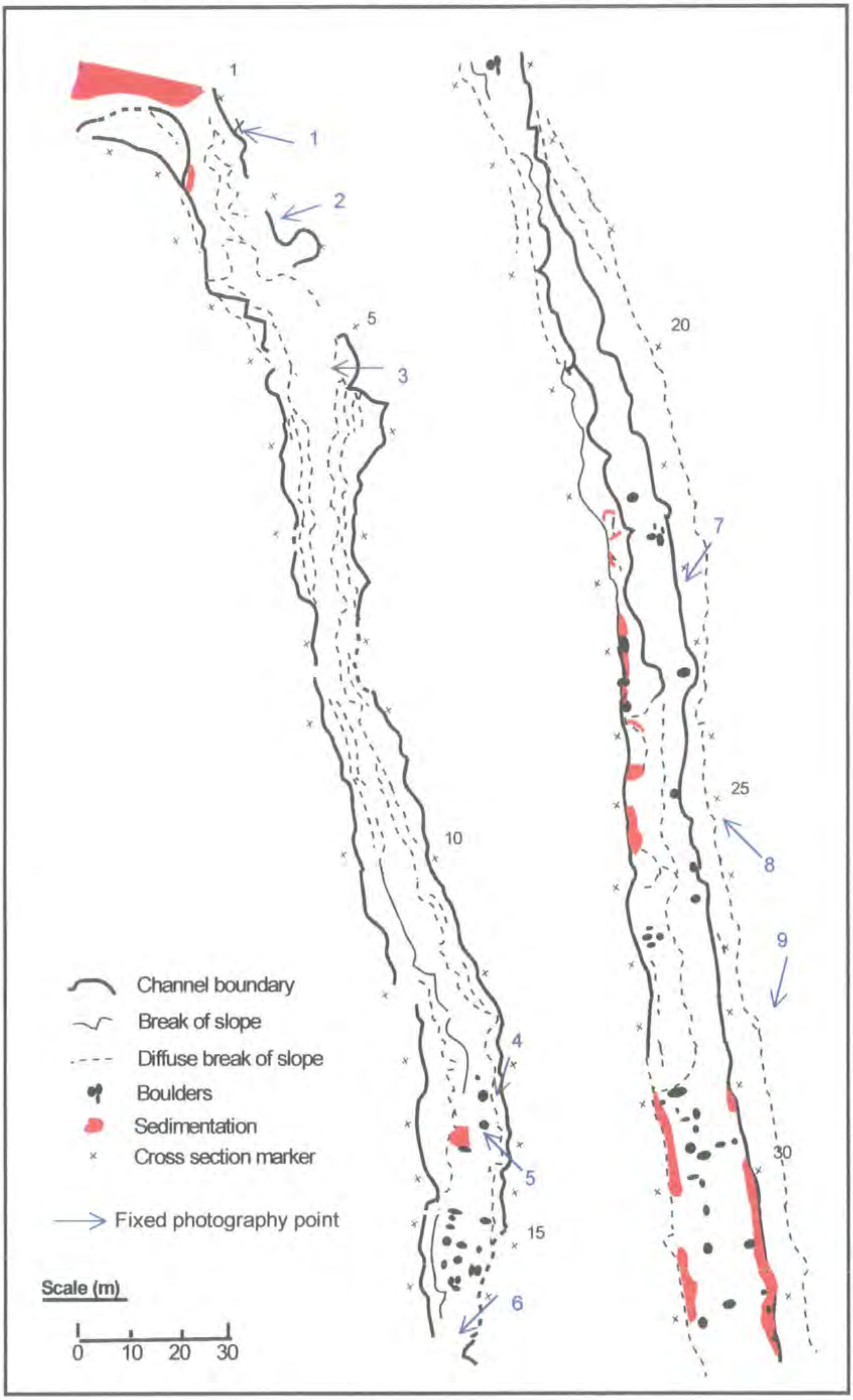


Figure 3.2 Detailed fieldwork plan

Figure 3.3 Geomorphic map illustrating the cross section and fixed photography points (20/11/02).



In this application geomorphic mapping provided an accurate and easily repeatable method of characterising changes in sedimentation in the channel.

3.3 Channel Cross Sectional Survey

Channel cross sectional surveys are frequently used in fluvial geomorphology, to determine channel change through measured changes in aggradation or degradation of the profile. Usually an initial survey is conducted to establish a base line which will form the datum from which to gauge change. Aggradation involves deposition of sediment across a cross section leading to raising of bed levels and consequent flow changes. Degradation is the removal of sediment and can also change the flow significantly depending on the volume of sediment removed. The cross sectional form can be measured in a variety of different ways (For example, EDM or simple levelling techniques). Both Weissel and Seidl (1998) and Pazzaglia *et al.* (1998) have used cross sectional and longitudinal survey techniques to study bedrock channels. However the accuracy of the survey is dependent on the level of detail which the study requires and often depends on the size of the research area.

Initially a complete survey of all 30 cross sections was undertaken at the start of the research (1/11/02) to enable a comparison of channel changes over the study period. The sections are spaced at 10 m intervals down the study reach which is approximately 300 m long. The average width of each section is 13 m. At each section a measuring tape was placed from a marker peg on the left bank to the marker peg on the right bank to record the distance across the channel. A level and a tripod were set up on the left bank, near the marker pegs. A five metre staff was used to record level height. Distances were measured using a tape or determined by stadia tacheometry.

Measurements were taken at 50 cm intervals or where a significant break of slope occurred. This produced a detailed representation of the cross section. Not every section could be surveyed from one station so the tripod was frequently moved down the bedrock section to complete all thirty cross sections.

The survey was repeated at the end of the study on the 30/6/03. Under the same controls and using the same points of reference. A longitudinal profile was also surveyed during the study on the 07/05/03. The profile was taken down the thalweg of the river channel along the full length of the study reach. To establish the detailed bed morphology, measurements were taken at steps in the bedrock and when a significant change of slope occurred within the floor of the channel.

The data from the cross sections was entered into a spreadsheet and cross sections drawn. All sections were levelled to a base datum so each cross section had the same basic reference point and changes in the channel over the study period could be documented.

3.4 Fixed Point Photography

Fixed point photography provides a visual comparison of channel change between consecutive photographs. The techniques are commonly used in conjunction with other methods such as geomorphic mapping or cross section survey. The photographs provide a record of channel morphology at a given time and provide a qualitative appraisal of sedimentary structures in the channel. This technique has been used in bedrock channel research by Carling and Tinkler (1998), Tinkler and Parish (1998) and Tinkler and Wohl (1998).

Along the study reach there are areas in which sediment is likely to accumulate for example in pool sequences, areas with low flow velocity and behind larger boulders. These zones were the focus of the fixed point photography. Photographs were taken at nine points along the bedrock section and the location of each photograph noted on the geomorphic map (Figure, 3.3). The network of photo points allowed a record of sedimentary changes to be built up over the fieldwork period.

3.5.Sediment grain-size surveys.

There are many different methods of sampling sediment. The grain size distribution of channel bed sediments may be characterised via bulk sampling or clast measurements. There are three main methods of sampling bed sediment: pebble counts, grid counts and areal samples. Methods such as the Wolman analysis (1954), random walk (Leopold, 1970) and visual comparison can all be used in the field to observe the size of clasts. The Wolman (1954) method of frequency counts is the most common. Pebble counts can also be collected along a line and a number of samples are hand-picked on a transect, (Bunte and Abt, 2001). This method is frequently used as an alternative to the Wolman grid. Sediment sampling techniques have been used in bedrock studies to determine grain-size by Carling and Tinkler (1998) and Cenderelli and Cluer (1998). In this study a stratified sampling framework based on channel cross sections was used to characterise changes in grain-size distribution. Sampling was undertaken from the proximal to distal ends of the reach. Table 3.1 shows a comparison of surface sampling techniques.

Table 3.1 Comparison of surface sampling techniques (Bunte and Abt, 2001, p276).

Pebble Counts	**Grid Counts**	**Areal samples**
Sample a present number of particles in wide and approximately even spaced increments of at least D_{mor} size	Sample a present number of particles under a grid of approximately D_{mor} size	Sample all surface particles within a small predefined sampling area
Cover a large sampling area	Sample several small areas within a reach or cover small areas of homogeneous sediment (facies patch)	Focus on point locations and require several samples to be taken within the sampling area
Suitable for gravel and cobbles not for sand	Suitable for gravel, not sand	Suitable for sand to medium gravel not for coarse gravel or cobbles
Long field time no lab time	Hand-picking long field time no lab time, Photographs short field time, long lab time.	Both field and lab time
Sampled particle sizes comparable with particle size from grid counts and volumetric samples.	Sampled particle sizes comparable and combinable with particle sizes from pebble counts and volumetric samples	Sampled particle sizes not directly comparable and combinable with particle sizes from pebble or grid counts or volumetric samples.

The cross sections used for the analysis were 1, 2 and 3 at the very top of the section, 14, 15, and 16 in the middle of the section and 28, 29 and 30 at the bottom of the section (Figure, 3.3). A measuring tape was placed across the section from peg to peg and the sediment sizes recorded across the sections. The method was repeated twice (18/12/02 and 3/7/03) during the fieldwork period in order to determine how sediment grain-size varied over time.

3.6 Tracers

The most common method for establishing how sediment moves in river channels, involves the use of tracers. Tracers show how sediment is redistributed both temporally and spatially. A tracer is a rock of a predetermine size which is marked in some way, e.g. a magnet is placed in a hole drilled in the rock and the rock is brightly painted.

When placed in the river tracers can provide a record of sediment movement. Magnetic tracers have been used in previous fluvial channel studies and are discussed by Bunte and Abt (2001) and Hoey (1992). Alternatively, Carling *et al.* (2003) have currently developed an impact sensor and plate which is fixed at the base of the bedrock channel during low flows. The small box contains a data logger which can detect the movement of a particle as small as a few millimetres. As particles move over the bed the logger is able to detect the difference between clast size. The logger is able to record the size of sediment which is moving along the bed at any stage. The aim of the new logger is to overcome difficulties in measuring changes of sediment in high velocity flows and the loss of expensive equipment. Test results have recorded boulders of over one metre passing over the logger.

Over two hundred pebbles and boulders were collected from the study reach according to the size range in the original sediment size survey on the 18/12/02. The original measurements recorded during the first survey were used to establish a representation size range for the tracers. When the tracers were seeded into the bar a survey of the bar sediment also was conducted. A sample size of 150 pebbles to boulders were measured. This allowed direct comparison between the sediment on the bar and the tracers. A bar survey were conducted at the end of the research. This included the original bar into which the tracers were seeded and two further bars which contained tracers at points downstream. Transects across the bar were measured at half a metre intervals and the sediment size touching the measuring tape was recorded. The samples were brought back to the laboratory and each individual rock drilled using a masonry drill. The rocks were then washed, cleaned and dried out. A magnet was placed inside the drilled hole and sealed with silicone gel to hold the magnet in place. The tracers were then painted in bright yellow masonry paint and numbered. Each rock was weighed and all three axis measurements were recorded.

The exact timing of tracer movement was monitored by a new technique. Selected tracers were linked to a state data logger. This involved drilling an extra hole for a switch to be fitted which would fix onto the data logger (Figure 3.4). The state logger is attached to the rock by using an easily triggered switch to try and minimise any alterations to the natural movement of the block. The logger is fixed above the river channel and a wire form the logger attached to the rock (Figure 3.4). The logger records two states either open when the rock is attached or closed when it moves downstream.

In the field a further fifteen larger boulders were painted to provide a representative sample of the larger sediment which was found in the original sediment analysis study. The 150 tracers (Figure 3.5), which were prepared in the laboratory, were seeded into a bar which had formed part way across the channel just below cross section 5 (Figure 3.3). Measurements were taken from the bar downstream, using a series of measuring tapes the position of any tracers which had moved were noted at each point. The measuring tape was placed at the end of the bar and fixed in place; the tape was then extended down the middle of the channel. The points at which tracers were found were measured against the tape and the distance recorded.

A pressure transducer was also set up in the bed just downstream of the entrance bar to record river stage. The data logger was position at the top of the gorge section and the cable placed in a fissure in the bedrock. The cable was fixed in place to prevent movement in high flows using metal brackets and drilled into the bedrock. The tip of the transducer was protected using a plastic sheath.

Figure 3.4 Methodology for the state logger.

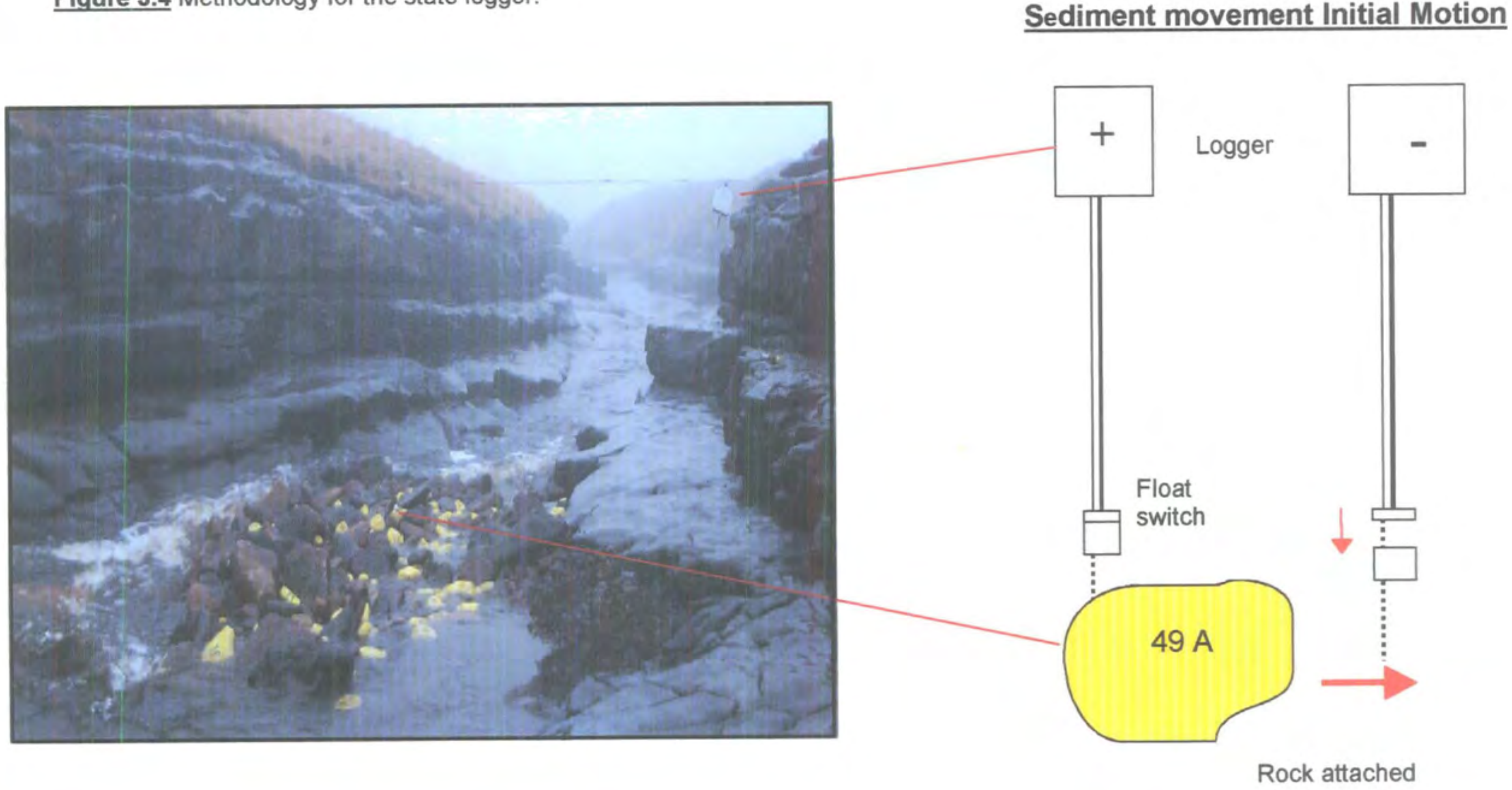


Figure 3.5 A comparison of the size distribution of tracers used in the study and the bar located at the tracer introduction point.

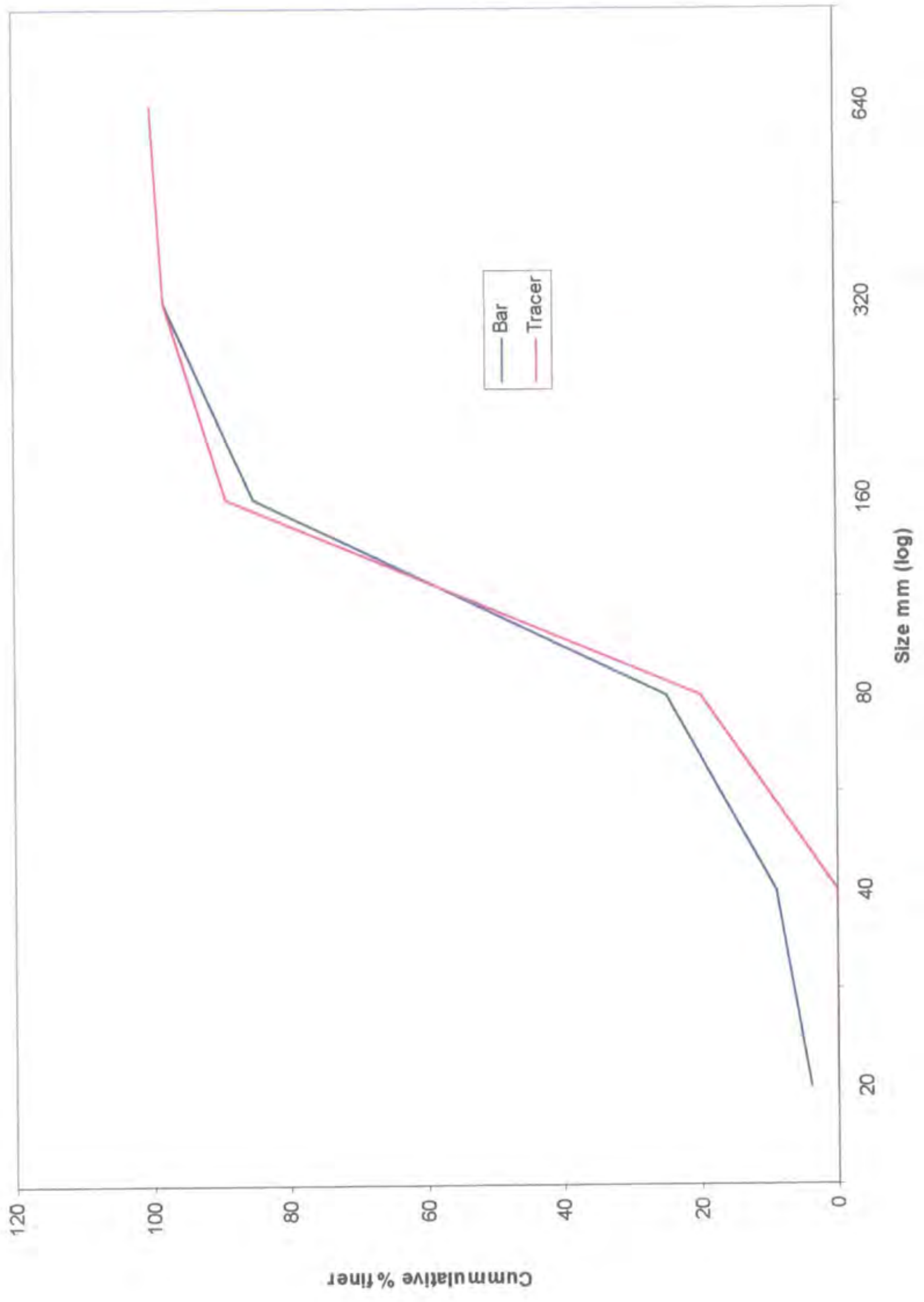
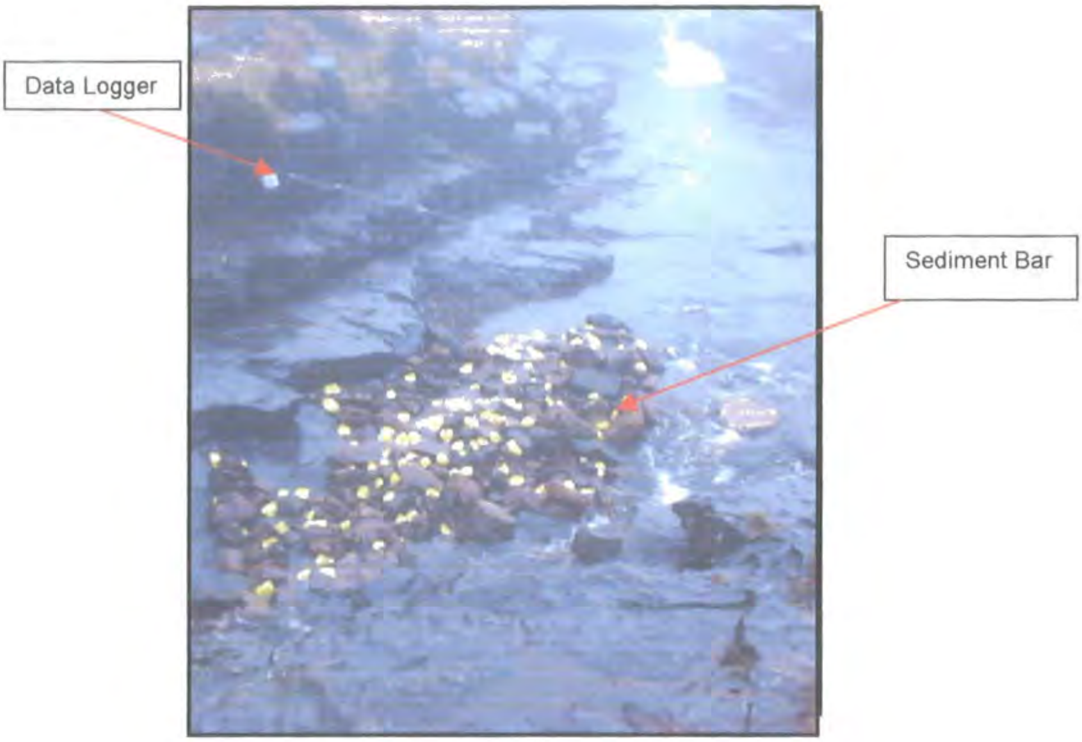


Figure 3.6 Upstream bar into which the tracers were seeded. The state data logger is suspended above the channel.



3.7 Bedrock Channel Classification

Definition of what exactly represents a bedrock channel is open to debate. Carling and Reader (1982) suggest that bedrock channels may form in headwater tributaries, however bedrock channels are not solely limited to these parts of the fluvial system. Howard (1980, 1998) states that bedrock channels are found in mountainous regions and lack bed sediment, this is a very general statement and hard to quantify. The most useful definition of a bedrock channel, to date, is that proposed by Tinkler and Wohl (1998), in which they suggest that a substantial proportion of the boundary $\geq$ 50% is exposed bedrock or is covered by a thin alluvial layer which may be mobile under high flows. This definition is more precise than the previous ones however it is still very general as bedrock channels cover a range of forms.

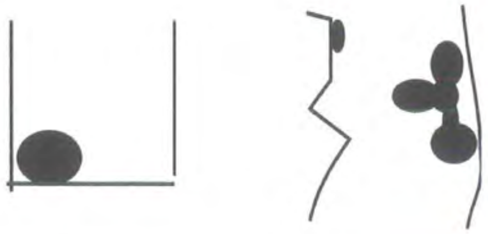
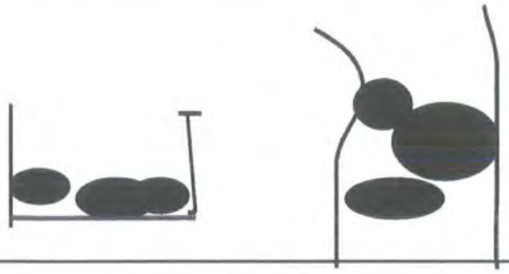
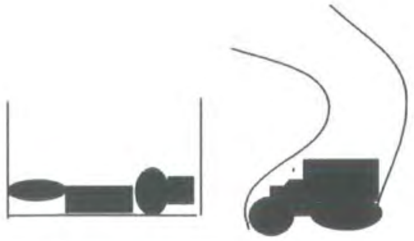
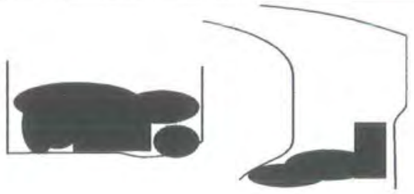
Alternative definitions should acknowledge that the degree of sediment cover determines the local morphology and the impact on the flow and processes operating in the channel.

The new scheme proposed here attempts to classify bedrock channels in to five different categories from bare rock through to a full alluvial channel. The scheme aims to characterise variety within bedrock channels in a more detailed way (Figure 3.7). Both Trout Beck, which contains the study reach, and the Upper Tees, were classified according to the system outlined in Figure 3.7. The aim was to show the proportion of the different classes of bedrock channel and their relationship to alluvial channel reaches in the Tees and Trout Beck catchment areas. The length of the river channel on each river was mapped. Where a change in bed classification was observed the position was recorded using a Magellan 12-Channel G.P.S and the classification type recorded. Photographs were taken to show the difference in classification on both channel reaches. This process was repeated down the length of the main trunk channels of Trout Beck and the Tees (Figure 1.1 Bold Line). Small tributaries were not classified.

3.8 Flume Experiments.

Flume experiments provide a physical, manageable small-scale representation of a bedrock channel environment. The change in scale requires a corresponding change in the scale of the forces represented in the flume system. The direct study of bedrock channel processes in the natural environment is extremely difficult due to high magnitude events (Thompson and Wohl, 1998). The larger the flume the more realistic the field conductions (Williams, 1971). As the flume size decreases complications from channel walls (Williams, 1970) and inappropriate approach conditions begin to affect the quality of results (Williams, 1971).

Figure 3.7 Bedrock channel classification scheme

	Bed Categories	Bank Categories	Diagram	Photograph illustration
1	Bare Rock, exposed both horizontally and or vertically.	Bedrock/alluvium		
2	Bare rock visible, however depositional features are present in the form of small sediment clusters or bars. The feature may cover up to half the channel width. This is dependent on the constraints of the bedrock both horizontally and vertically. Rock steps and gorges will often be important in such reaches.	Bedrock/alluvium		
3	Sediment is found to be discontinues across the full channel width, with frequent small patches of bedrock visible. Evidence of bedrock channel may also be dependent on horizontal control e.g. signs of bedrock abutments at the edge of a channel.	Bedrock/alluvium		
4	A continuous layer of sediment across the channel width, no bedrock visible under low flow. However sediment depth of approx 10 cm allows for the bed to be highly mobile under high flow conditions and bdrock to be exposed and exerted a topographic control.	Bedrock/alluvium		
5	Full contemporary alluvial cover up to 1m thick	Alluvium		

For the experiments reported here a recirculatory glass-sided tilting flume was used. It had a rectangular cross-section 150 mm wide by 450 mm deep and a working section length of approximately 5m. Water circulation is by a centrifugal pump mounted beneath the underframe. Slope is adjusted by means of a pivot foot and jacking mechanism, a manual valve and tailgate control flow rate. The smooth painted flume bed was used for the bed step experiments. Test blocks were cut from sandstone, The maximum size of block was 5 cm, which was thought to be the largest size possible which still minimised interference from the flume walls.

The flume study concentrated on examining block movements at a bed step. Velocities were to be recorded as the blocks were gradually moved away form the bed step. A large plank of wood was cut to 1.85 m, and then placed at the top of the flume to simulate a bed step. The flow was held constant for all four block sizes, at a 49.5 m s^{-1} velocity profiles were taken at 2 cm intervals along the flume and the block was gradually moved away from the step at set intervals. The intervals remained roughly constant for each block size, ¼ , ½ , ¾, 1, and double the block width. This approach was used to try and establish detailed velocity profile before movement, to try and ascertain the exact point of movement for each block type. The distance at which each block size was entrainment and deposition was recorded.

In the field, rock step surveys were completed on two bedrock steps in the Trout Beck reach. Each survey used the method of intersection using two measuring tapes fixed at specific points to locate the positions of the step, detached blocks and the channel banks.

3.9 Summary

This research uses a variety of methods. These include both cross sectional and longitudinal profiles, fixed point photography and geomorphic mapping. The techniques used provide reach scale data and monitor specific points to gather evidence for re-sedimentation over the study period. Sediment movement within the channel was monitored using a tracer experiment and repeated sediment surveys. The stage data collected from the tracer experiments can be used in conjunction with the tracer results, to investigate sediment transport within the bedrock channel. Flume experiments were undertaken using a novel simulation of a bedrock bed step. Different block sizes were tested to determine movement patterns at different positions away from the step. The data collected from the flume experiments was also collaborated with field data collected form two natural bedrock steps. Finally an overall classification scheme was developed which allows the river channel to be mapped in the context of a scale of sedimentation within bedrock channels, this was applied to the whole Upper Tees catchment on the main trunk channel.

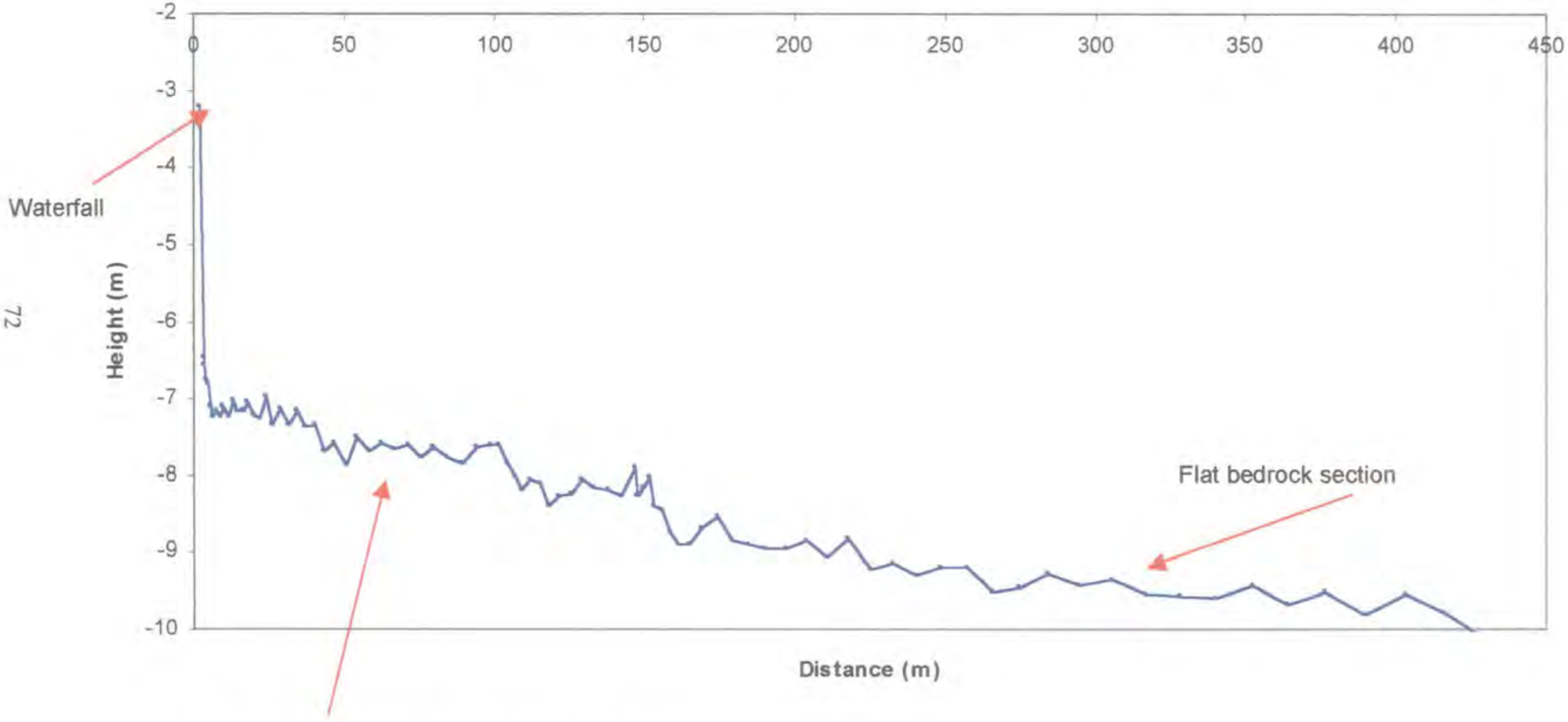
4.1 Introduction

This chapter presents results obtained from the analysis of sedimentation changes in the Trout Beck study reach. Firstly the chapter concentrates on the full study reach analysing the results from cross sections, geomorphic mapping and fixed point photography. The chapter then focuses on smaller areas of the reach where information on, specific cross sections and bars were collected. A section of data comprising the rock step data from the field and data from flume experiments is then presented. The chapter concludes with a summary of the results obtained from the tracer data.

4.2 Channel Cross Section Surveys

Channel cross section surveys were conducted at the start and finish of the research period. They provide an indication of how the study reach section has changed over an eight-month period. Figure 4.1 shows the long profile of the study reach. The large initial drop is the waterfall at the head of the channel. In the initial bedrock gorge section there are several step-pool sequences. The gorge section ends with a large pool and the bedrock begins to flatten out. The pools become fewer and also shallower and extended in length. They provide an indication of how the study reach section has changed over an eight-month period. Figure 4.3 shows the net change in storage at each of the cross sections. Within the reach there appears to be several zones of change. The first three sections (1-3) experience a sediment loss, the following three a gain (4-6). The channel then appears to have remained stable with only small amounts of change until a significant loss of sediment is recorded in the middle of the reach between sections 11-15 (Figure 4.2). This in turn is followed by sediment accumulation all the way through to section 22 afterwhich sediment changes appear to be more erratic.

Figure 4.1 Long profile of study reach section



Waterfall

Flat bedrock section

Middle of bedrock gorge section of reach

Figure 4.2

Cumulative gain and loss of stored sediment in the study reach.

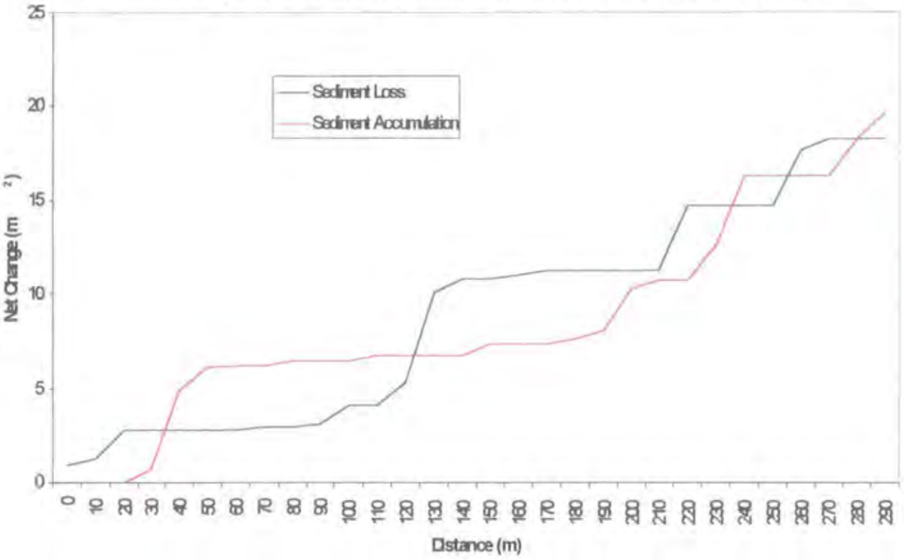


Figure 4.3

Net change in sediment storage down the study reach

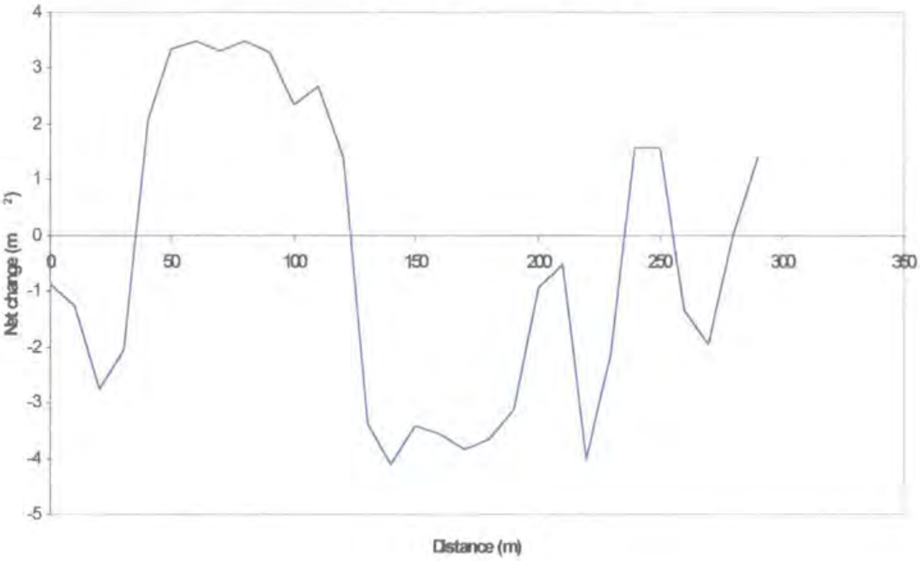


Figure 4.4 shows cross section 26 in the study reach which has remained virtually stable throughout the research period. There appears to be no accumulation or deposition of sediment on this section, possibly due to the plane bedrock bed and alluvial banks. The channel is concentrated in a narrow (0.8m) deep channel on the right hand side of the channel, so the majority of process activity is concentrated in this area allowing for minimal change to occur over the actual width of the channel. Over the year in the plane bed section of the reach the only change has involved aggradation of only very fine sediment (dominantly silts) to depth of approximately 10mm.

Figures 4.5 and 4.6 show two very different types of channel degradation. Figure 4.5 shows a large loss of sediment either side of a rise in the middle of channel section 14. The net loss of sediment from cross section 14 is the largest within the reach as a whole. Within this section small changes in sediment loss can be observed on the left hand side of the cross section. On the right side there is a large area of degradation which may be due to the removal of boulders and smaller sediment within one of the flood events. Figure 4.6 illustrates a different pattern of sediment degradation. The channel within this section remains largely unchanged, however there is sediment removal from the right hand bank; possibly due to the removal of a large boulder on the right hand bank during a flood.

There are many different types of resedimentation within the channel. Figure 4.7 demonstrates small changes over the survey period. On the right of the channel a small volume of sediment has accumulated on the ridge and next to a bedrock ledge at the top of the channel section.

Figure 4.4 Cross section 26, illustrating a stable channel with very little change

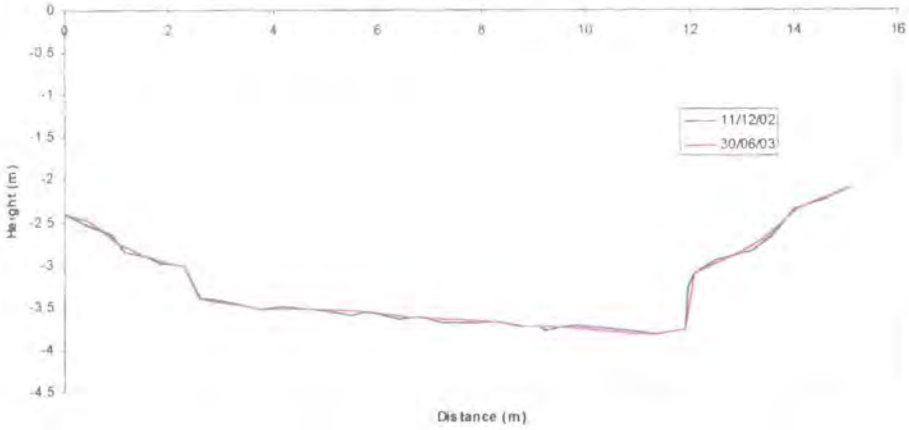
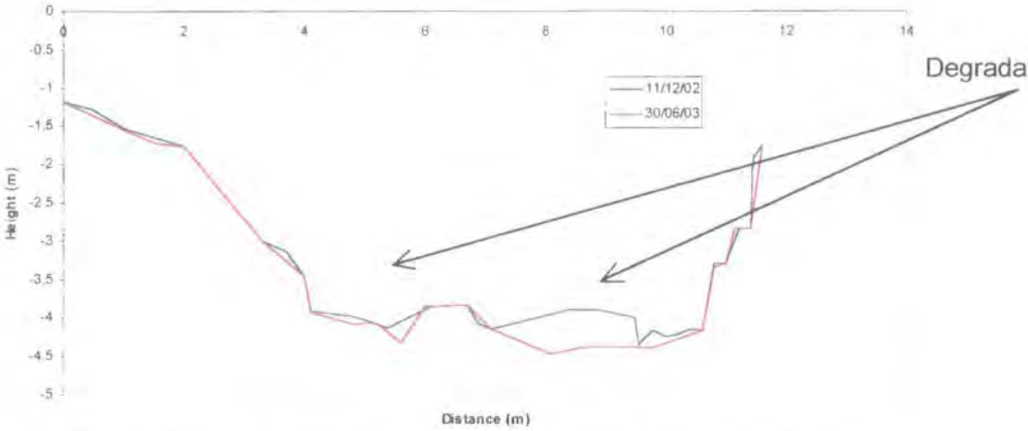
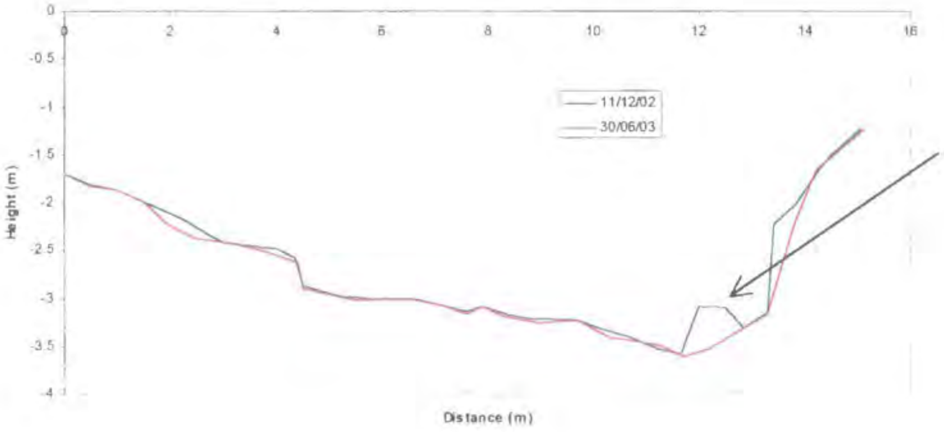


Figure 4.5 Cross section 14, illustrating channel degradation



Degradation

Figure 4.6 Cross section 23 – illustrating channel bank erosion and loss of a boulder



Loss of boulder

Figure 4.8 illustrates a large area of sediment accumulation over much of the channel bed. There is evidence of deposition of a large boulder in the deepest part of the channel and a small cluster of sediment. There appears to have been a build up of sediment in the centre of the channel and on the left hand side. Figure 4.9, cross section 27, demonstrates the largest changes within the study reach. This section was found to be the least stable and has undergone many changes. This section occurs at the end of the bedrock reach, on the margin of the alluvial reach. This section shows a large volume of sediment accumulation of the left hand side of the channel. This consists of a large boulder with smaller sediment accumulation around and behind it. Within this section a large boulder (over 1 m in diameter) has remained in the centre of the channel over the study period but on the right hand side of the section a local area of sediment loss is evident.

4.3 Fixed Point Photography

Figure 3.3 shows the fixed photography points in the study reach. The photographs were taken at intervals (13/02/03, 25/03/03, 2/04/03, 28/05/03, 3/07/03) over the year (Figure 3.2). Figure's 4.10, 4.11, 4.12 are taken at fixed photography point 1(Figure 3.3). The river is at the entrance to the bedrock gorge. On the left there are bedrock banks and on the right there is alluvial sedimentation on a bedrock bench. Initially sediment storage is low (Figure 4.10). However in Figure 4.11 taken a few months later, small areas of resedimentation can be seen to the right of the main channel. The final photograph taken in July 2003 shows another slight increase in the level of sedimentation (Figure 4.12). The sedimentation appears to be occurring in sheltered areas away from the main flow or behind large boulders within the bar. In general changes are small over the five-month period of observation.

Figure 4.7 Cross section 7 – illustrating resedimentation of the right side of the channel

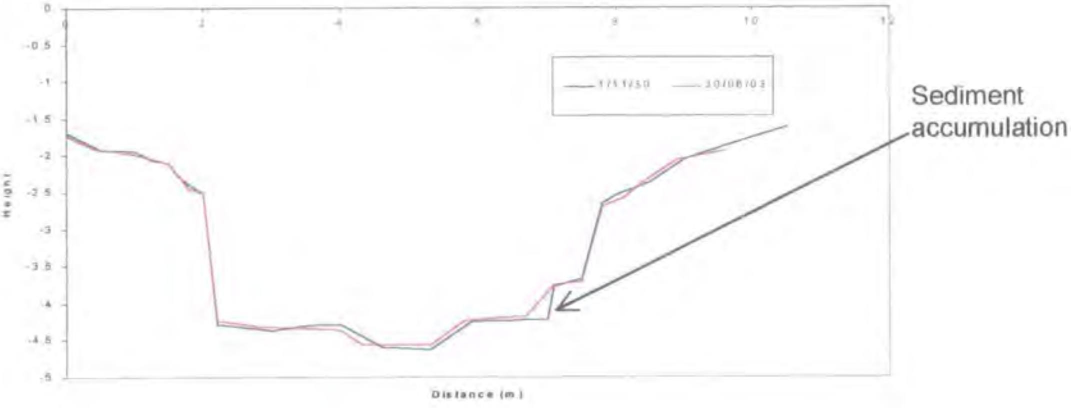


Figure 4.8 Cross section 21- illustrating resedimentation across the channel bed.

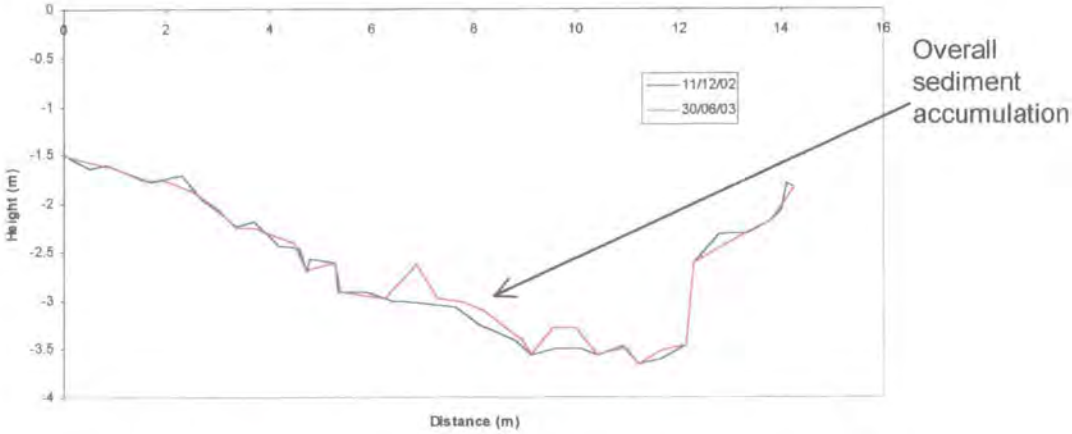


Figure 4.9 Cross section 27 – illustrating channel instability with an area of resedimentation of the left side of the channel.

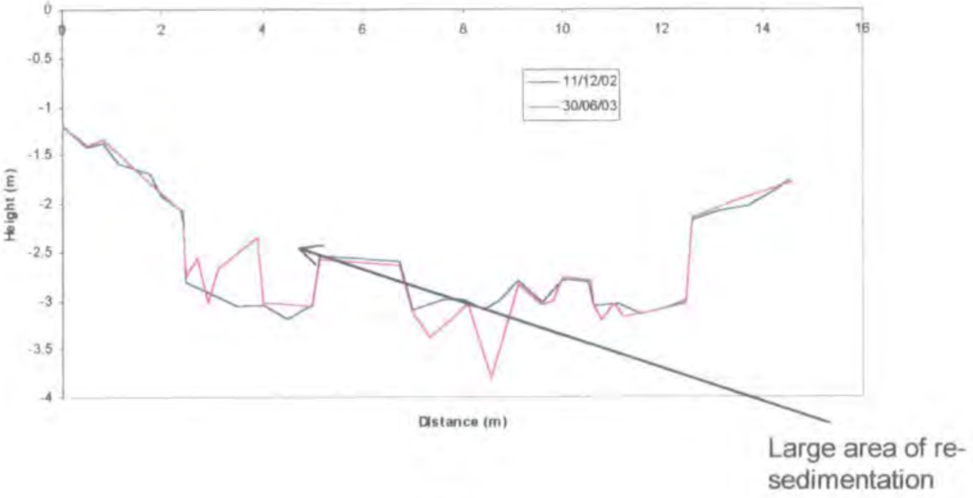


Figure 4.10 Fixed Photography Point 1 13/02/03 (NY 74995 33088)

Figure 4.11 Fixed Photography Point 1 – 8/05/03

Figure 4.12 Fixed Photography Point 1 – 3/07/03

Figure's, 4.13, 4.14 and 4.15 are taken at cross section 5 of the study reach (Figure 3.3). The photographs show a bar which has accumulated in a bedrock step section of the river. There is a bedrock rise, which at low flow obstructs flow downstream (Figure, 4.13). Figure 4.14 shows the sediment bar, (where the tracers were seeded), with small areas of deposition having occurred in two main areas of the bar. Figure 4.15 however shows a considerable reduction in bar area when compared with the original photograph (Figure 4.13). Although many of the larger boulders remain, much of the smaller sediment has been removed.

Figure's 4.16, 4.17 and 4.18 are taken between cross sections 13 and 14, at fixed photography point 5 (Figure 3.3). The site is at the end of the bedrock gorge section where the river bends slightly. In Figure 4.16 there are two main areas of sediment accumulation, one on the left, downstream of the step-pool sequence and one on the right, around a large boulder. In Figure 4.17 there appears to be little change on the right but an increase in sedimentation on the left. The increase in sediment on the left bar is also observed in Figure 4.18 where an accompanying change in sediment is also seen on the right. Sedimentation has also occurred behind the large boulder downstream of the small step.

The final fixed point observation post on the bedrock section occurs at cross section point 24, fixed photography points 8 and 9 (Figure, 3.3). This point shows the flat plane-bed bedrock section which occurs at the end of the gorge section. Very little large sediment can be seen (Figure 4.19), however there is an abundance of fine sediment ranging in size from silt to fine gravel. In Figure 4.20 the amount of fine sedimentation appears to have increased slightly. However in Figure 4.21 the level of fine sediment has been reduced again.

Figure 4.13 Fixed Photography Point 3 – 13/02/03 (NY 75027 33148)

Build up of sediment behind a bedrock rise (Part of the Bed)

Figure 4.14 Fixed Photography Point 3 – 8/05/03

Deposition of sediment

Figure 4.15 Fixed Photography Point 3 – 3/07/03

Areas of sediment removal

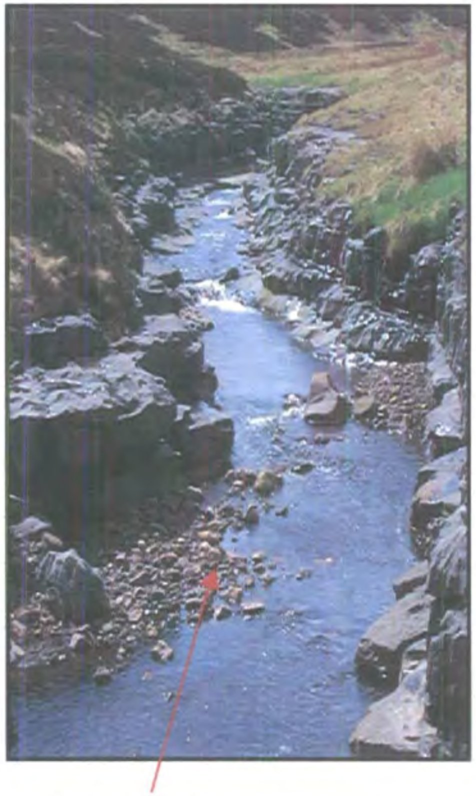
Figure 4.16

Fixed Photography Point 5 – 13/02/03 (NY 75055 33162

A

Figure 4.17

Fixed Photography Point 5 – 8/5/03



Sediment build up

B

Figure 4.18

Fixed Photography Point 5 – 3/07/03

Continued sediment build up

C

Figure 4.19

Fixed Photography Point 8 – 13/02/03 (NY 75125 33241)

Figure 4.20

Fixed Photography Point 8 – 8/5/03

Figure 4.21

Fixed Photography Point 8 – 3/07/03

In Figure 4.21 it can also be seen that some larger sediment that was close to the banks has also been removed from the section. This area of bedrock is very susceptible to redistribution of fine sediment during even modest flood events.

4.4 Geomorphic mapping.

Figure 4.22 shows the geomorphic maps of sedimentation in the study reach over the nine month observation period. Following the 30 July 2002 flood all sediment with the exception of a few large boulders was stripped from the reach. On the 11/12/02 very little sediment was recorded in the channel. The sediment was distributed mainly at either end on the channel. On the 18/12/02 some sedimentation had occurred in pockets at the head of the reach. Sedimentation had begun to occur in the middle of the channel with the growth of three proto-bars. The lower part of the reach showed only a slight increase in sediment on parts of the flat bedrock section (Figures 4.19, 20,21).

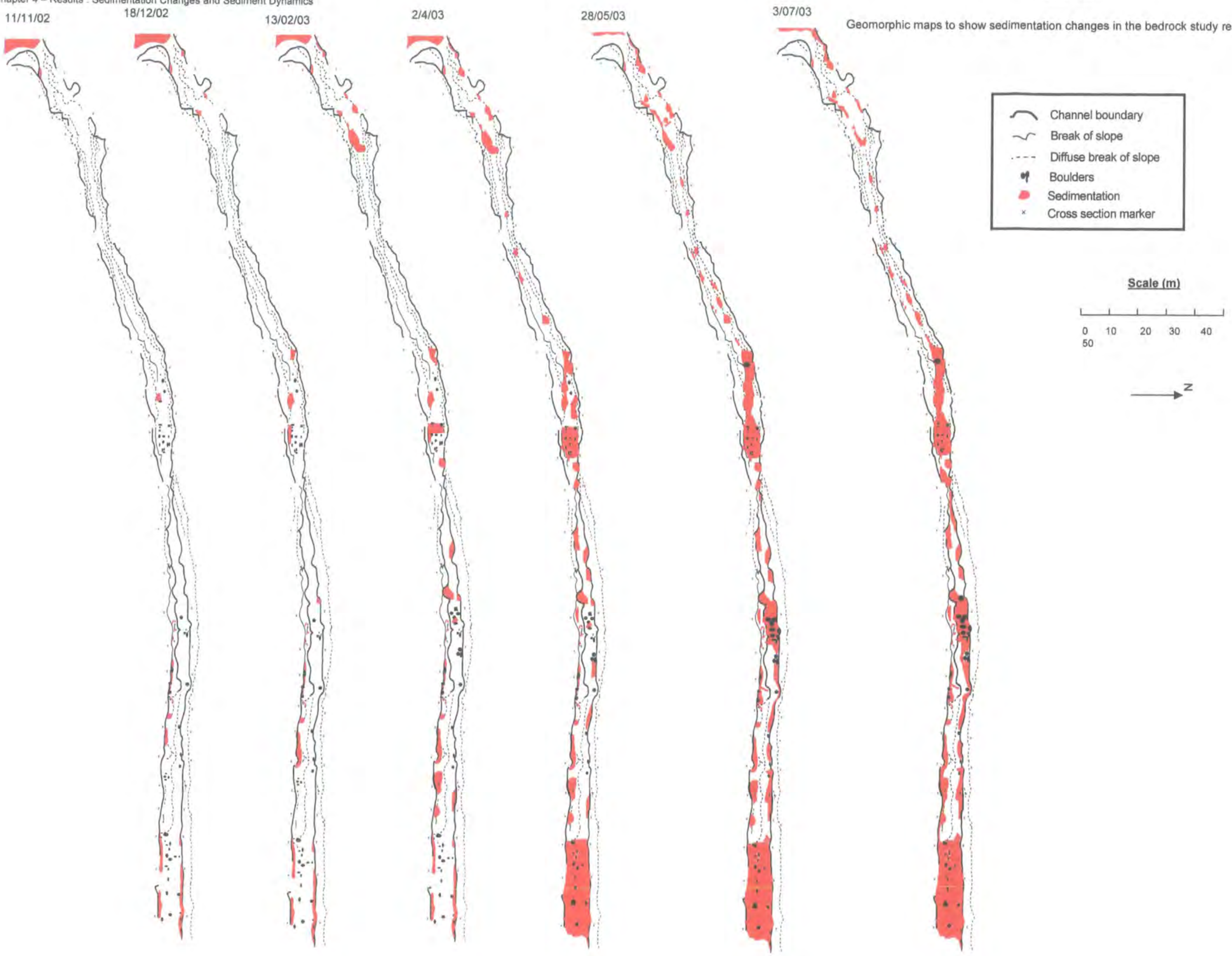
By the 13/02/03 a large area of sediment had accumulated in the upper section which extended all the way across the low flow channel. In the middle of the reach sedimentation had increased with sediment distributed across the whole channel width. Lower down the reach smaller areas of sedimentation also occurred . At the end of the reach sedimentation continued to develop laterally slowly expanding inward to the channel and also in an upstream – downstream direction along the margins.

The map for the 2/04/03 illustrates a large increase in sedimentation. A small amount of sediment has been deposited in the upper reaches and along the bedrock gorge section of the reach. The sediment bars in the middle of the reach are merging into one large fully sedimented area. Increased sedimentation has also occurred in the lower part of the reach with many more small pockets of sedimentation and the development of a fully alluvial reach at the distal end. This pattern is continued up until 28/05/03. The map shows some local adjustment in sediment in the upper half of the reach.

The bar at the top of the reach is slightly eroded, as is the bar just before the narrow gorge section at section 5 (Figure 4.22). Sediment had also accumulated within the bedrock gorge section of the reach with small clusters appearing. The bars in the middle of the reach have merged together to produce an area of significant sediment storage. Many larger rocks have been deposited in the lower reaches which were not originally there. Some have been transported from the middle section of the reach which has lost some of the larger boulders. Sedimentation has resulted in the merging of sediment storage areas and lower down the reach the lateral deposition of sediment has increased, slowly decreasing the amount of bedrock exposed within the channel.

Figure 4.22

Geomorphic maps to show sedimentation changes in the bedrock study reach



The final map (3/07/03), illustrates slight sediment loss from the upper reaches. The bedrock gorge and middle reaches appears no to have under gone little change and remained relatively stable. Lower down sedimentation has led to the merging of bars to produce a contiguous sediment sheet which almost completely fills the channel. The lower stretch of the reach has also remained stable since the previous mapping.

A comparison of the maps of 11/11/02 with 03/07/03 shows a channel with virtually no stored sediment to one which has a cover of approximately 30%. Overall two different patterns of sedimentation appear to be occurring within the channel. In the middle of the reach small bars form which grow and then merge together to form large areas of sedimentation which then gradually fill the channel. In the lower section of the reach lateral sedimentation appears to slowly thicken inwards until it meets slowly covering the channel with sediment.

The results from geomorphic mapping correlate reasonably well with those obtained from the cross sections. In the upper reaches of the study reach initially there is a small loss and then a large gain over sediment recorded over the year. The mapping shows a small gain of sediment in selected pockets and a larger gain of sediment below the waterfall area. In the gorge section the overall change recorded by both the cross sections and also the mapping shows very little change over the year (Figures 4.2,3). At the end of the gorge this area when mapped showed large changes in sedimentation with the amalgamation of several bars over the course of the year. However the cross section analysis records a loss in this section of the study reach. This may be because the cross sections cover a small specific area of channel whilst the spatial mapping represents the change in the channel as a whole. Geomorphic mapping confirms that sedimentation is occurring particularly at the end of the study reach and also at the top of the plane-bed section (Cross Sections 18-21).

4.5 Sediment Sample Surveys.

4.5.1 Sediment grain-size analysis on selected cross sections.

Figure 4.23 illustrates the differences in b axis size between the two surveys. The initial survey was completed on the 18/12/02 and the resurvey on 28/05/03. It was found that there was an overall increase in the size of the stored sediment .The most significant increases in b axis were observed between 150 mm to 400 mm. Increases can also be seen between 80-130 mm. A large decrease was seen in the small categories of 5-20 mm, other small decreases were recorded in three other categories.

4.5.2 Sediment grain-size analysis on selected bars.

Figure 4.24,5,6 illustrate downstream variation in b axis particle size on selected bars. The bars are at cross sections 5, 11 and 13, where most of the tracers were deposited. Initially small sizes seem to occur at either ends of the bar (0.5 m and 3 m downstream) with larger sediment in the middle of the bar between 1.5 m and 2.5 m downstream. These categories also contain the highest frequency of sediment between b axis size 40 - 60 mm.

The bar on section 5 shows a range of larger sediment 200-470 mm in which much smaller sediment is trapped behind (Figure 4.24). The bar on section 11 shows a cluster or larger rocks 2.5 to 3 m downstream of the initial starting point of the bar (Figure 4.25). Behind the cluster of sediment there is a gradual build up of small sediment then larger sediment in an upstream direction.

Figure 4.23 Differences in sedimentation on selected cross sections from the upper, middle and lower reaches of the study area on the 18/12/02 and 28/05/03

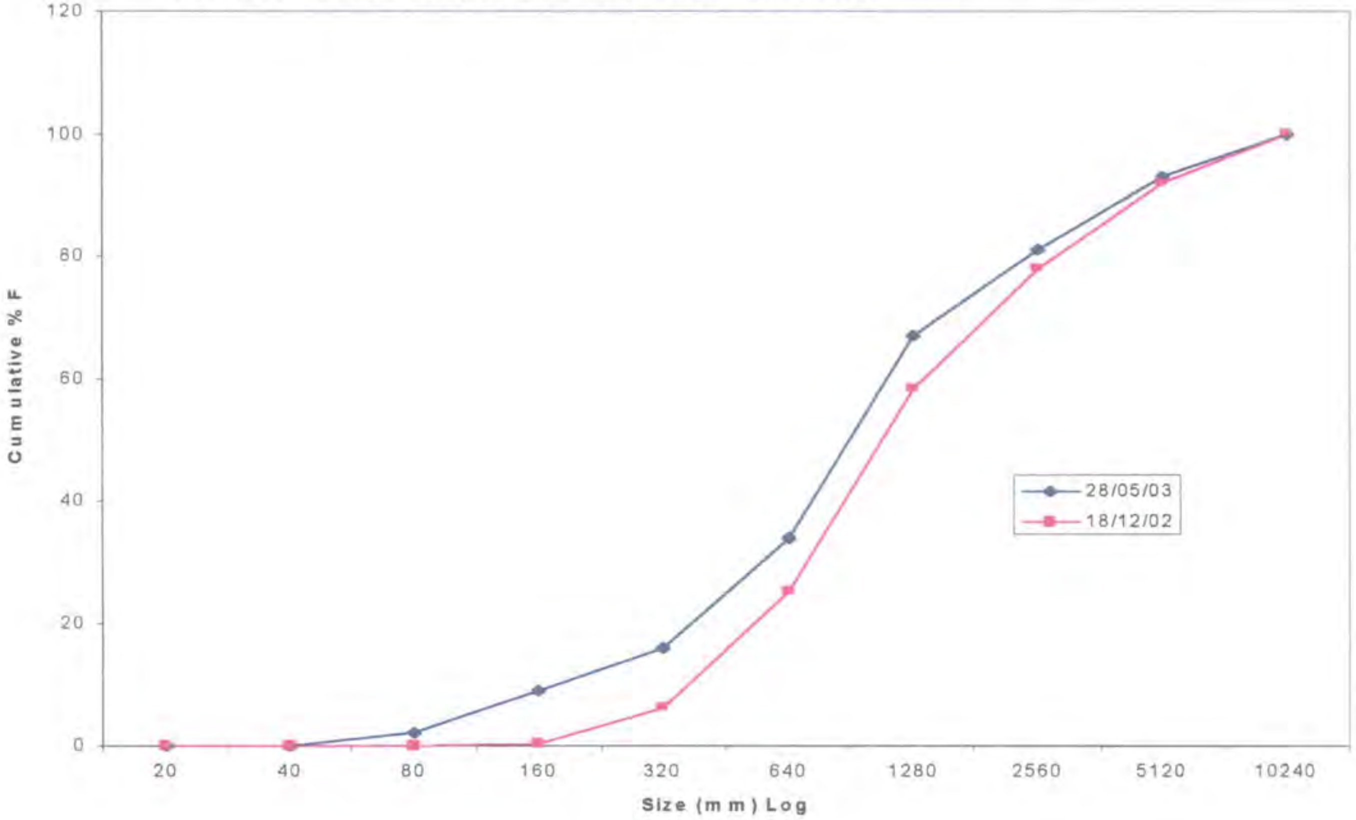


Figure 4.24 Grain size distribution on a sediment bar located at cross section 5.

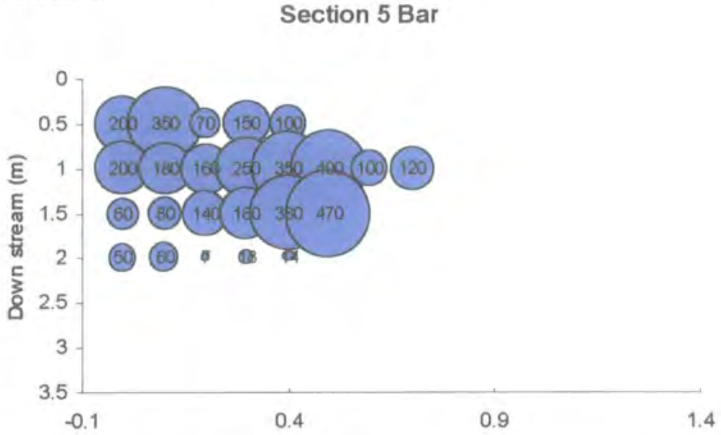


Figure 4.25 Grain size distribution on a sediment bar located at cross section 11

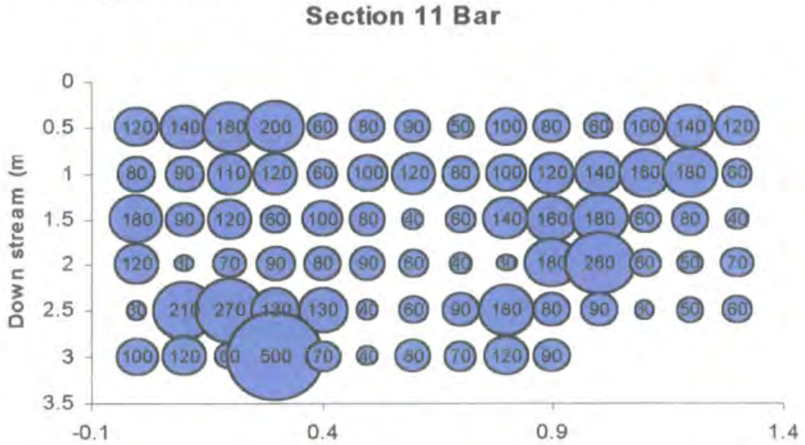
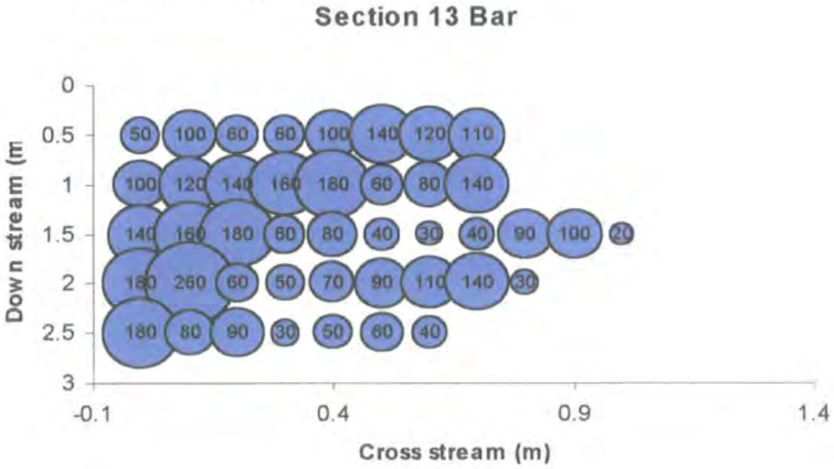


Figure 4.26 Grain size distribution on a sediment bar located at cross section 13



The final bar surveyed was on cross section 13 (Figure 4.26). In this bar much of the larger sediment is close to the banks in a circular pattern. The smaller sediment forms on the outskirts of this band of sediment (140 – 260 mm).

4.6 Tracer Study

4.6.1 Long profile

Figure 4.1 illustrates the long profile of the study reach. The pools in the bedrock gorge section are small in length however appear to be quite deep. The long profile is interesting when compared with the tracer data as many of the tracers were deposited within the pool area as shown in Figure 4.1. There were some tracers deposited in small pools in between the sediment bar and also the large pool which contains approximately 80% of the tracers.

4.6.2 Stage Data

Figure 4.27 illustrates the stage data obtained over the study period. The logger was set up just downstream of the seeded tracers on the sediment bar. The data shows many fluctuations in stage over the study period and three significant events which are likely to have influenced the tracer movement. The events are from 13/2/03 to 18/03/03 (Event 1), 8/5/03 to 28/05/03 (Event 3) and 28/05/03 to 19/06/03 (Event 4).

Figure 4.28 illustrates the results obtained from the state logger, both these events recorded were towards the end of the study period. Two further events in which some movement was recorded are shown in Figure 4.28 together with the stage data

Figure 4.27

Periods of measured tracer movement, together with the movement of the state logger clast Events numbered 1 and 2

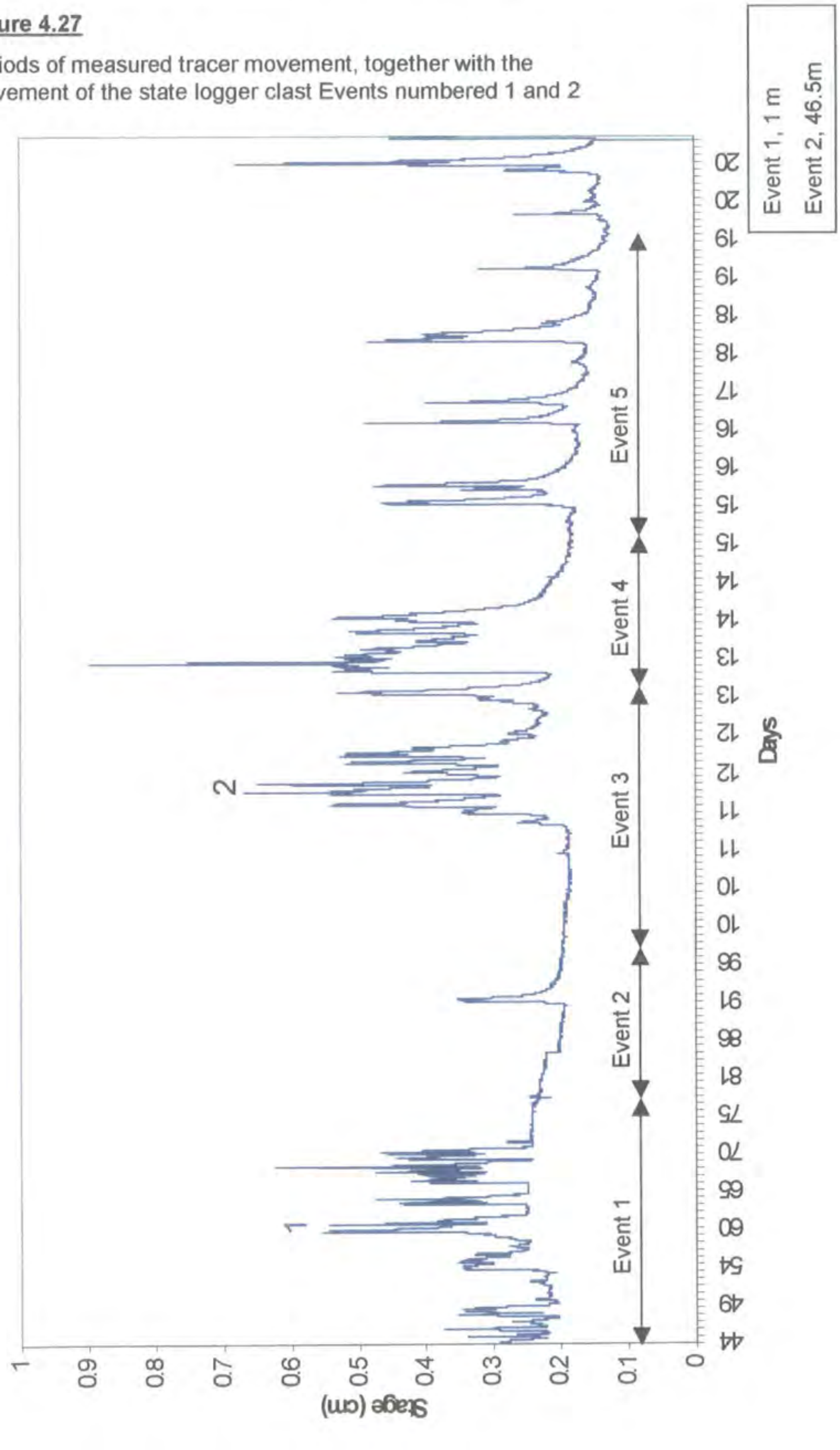
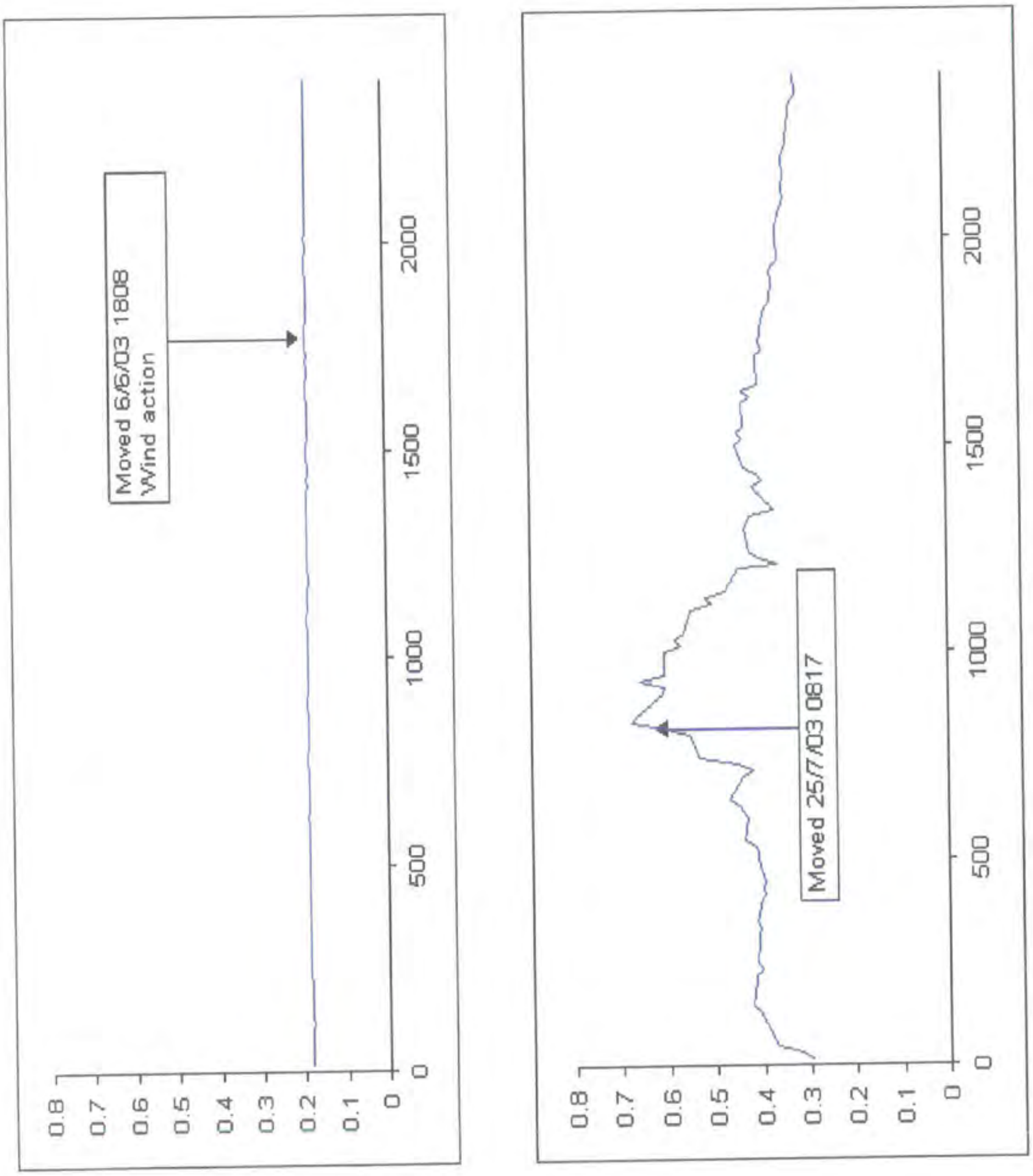


Figure 4.28

A detailed record of the state tracer movement



Moved 6/6/03 1808
Wind action

Moved 25/7/03 0817

In the cases when the state logger was triggered one occurred on the rising limb of a flood hydrograph and the other occurred following a period of low stable discharge. In this respect one can be considered a response to flow the other is a spurious recording possibly triggered by wind.

The tracers were seeded into a bar at the head of the reach (Cross section 5) on 13/02/03 and the last survey completed on 3/07/03. Figure 3.5 illustrates the sediment distribution on 18/12/02 for the bar before the tracers were seeded. The figure compares the b-axis size distribution of the tracers with the surface grain size of the bar. Many of the smaller clast sizes on the original bar are missing in the tracer distribution. On the bar there was a higher frequency of larger clast sizes (Figure 3.5) although all the large b-axis sizes are represented although they are fewer in number. The tracers chosen contained a larger number of b axis sizes in the 60 mm – 140 mm range than originally on the bar.

4.6.3Tracer Events

Figure 4.28 illustrates the stage data together with time when the tracers were measured. Figure 4.34 illustrates the distance travelled by the tracers in the observation periods. Figure 4.34 shows the b-axis of the transported tracers plotted against the distance travelled in each time period. In event 1 a small selection of tracers travelled between 20 and 60 m (Figure 4.29). In event 2 a larger selection of tracers (60) moved downstream with one tracer moving 180 m and the others between 0 and 60m (Figure 4.30). In event 3 there were several large tracers moved in this event and the mean distance travelled was extended to between 0-80 m. The largest number of tracer movements is seen in event 3 (108) (Figure 4.31). Event 4 recorded only a small selection of tracers moved about 60 m and a few moved 10m (Figure 4.32). However the total number of tracers which moved in event 4 were few. In event 5 there was virtually no change in movement by any of the tracers from the results obtained for event 4 (Figure 4.33).

Table 4.1 Total number of tracers moved in each event.

Event No.	1	2	3	4	5
Number of tracers moved out of 164.	31	60	108	121	121

Both Figure 4.29 and Figure 4.30, show a lack of tracer movement beyond 80 m this suggest accumulation of tracers in a specific area of the channel which may be a large sediment pool or behind a large step.

Figure 4.35, 36 illustrates the mean, upper and lower quartiles of each event. Figure 4.35 illustrates the overall movement in number of tracers. It was found that events two and three had the most tracer movement with also the largest range of movement in these two events. It was found that events four and five had little movement. Figure 4.36 illustrates the distance downstream which the tracers moved. In events one and two the end point of the tracers appeared the same with a range of tracers moving through out the reach. In events three, four and five the end point again was the same for each event, however in events four and five there was little movement until 65 m downstream of where the tracers were originally seeded. Events 3, 4 and 5 demonstrate a small range which suggests that the movement may be more confined and the sediment many be collected in one area of the channel and moving as a group.

Figure 4.29 Event 1 (18/03/03)

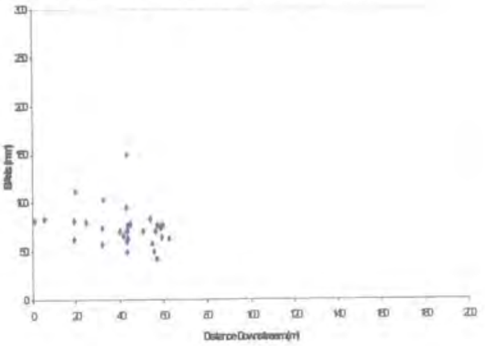


Figure 4.30 Event 2 (08/05/03)

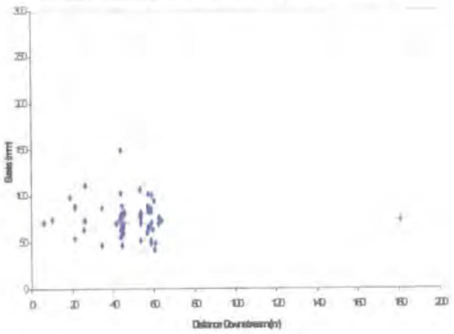


Figure 4.31 Event 3 (28/05/03)

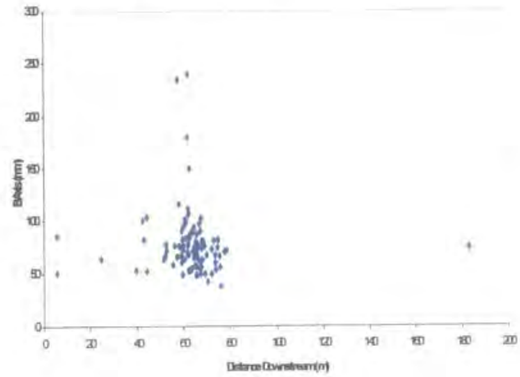
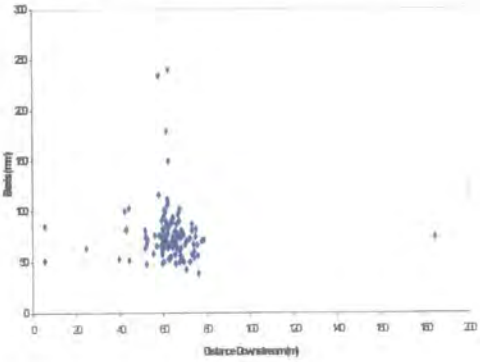


Figure 4.32 Event 4 (19/06/03)



Figured 4.33 Event 5 02/07/03

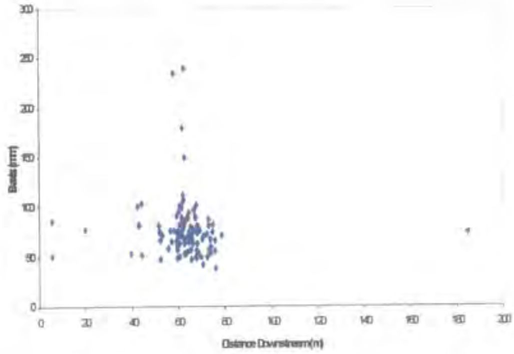
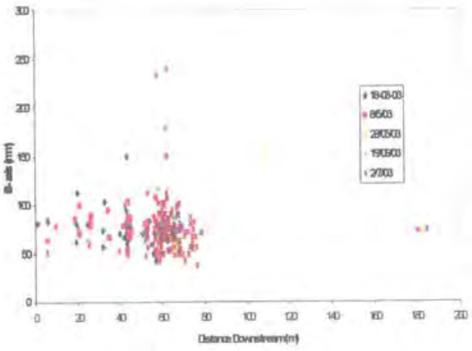


Figure 4.34 All tracer events



All graphs show distance downstream (m) against b axis (mm)

4.7 Influence of a bed step

An artificial bed step 3 cm deep was placed in the flume. A series of block transport experiments were undertaken. Blocks placed on the bed were moved sequentially away from the step until entrainment took place. The distance between the point of entrainment and point of deposition was measured. (Figure 4.37). Block sizes 3, 4 and 5 are entrained very close to the step in the full force of the water as it accelerates off the step. The 2 cm block was smaller than the step so the flow largely missed the block and the block was only entrained at the furthest distance away from the step when it become exposed from the shadowing effect. The 2 cm block also travelled the furthest distance once entrained, due to the lightness of the block as it was the smallest used in the experiments. The other three block sizes were entrained quite close to the bed step and all appeared to be entrained over a similar distance (Figure 4.37).

Figure 4.35

Box and Whiskers plots to illustrate movement of tracers during each event

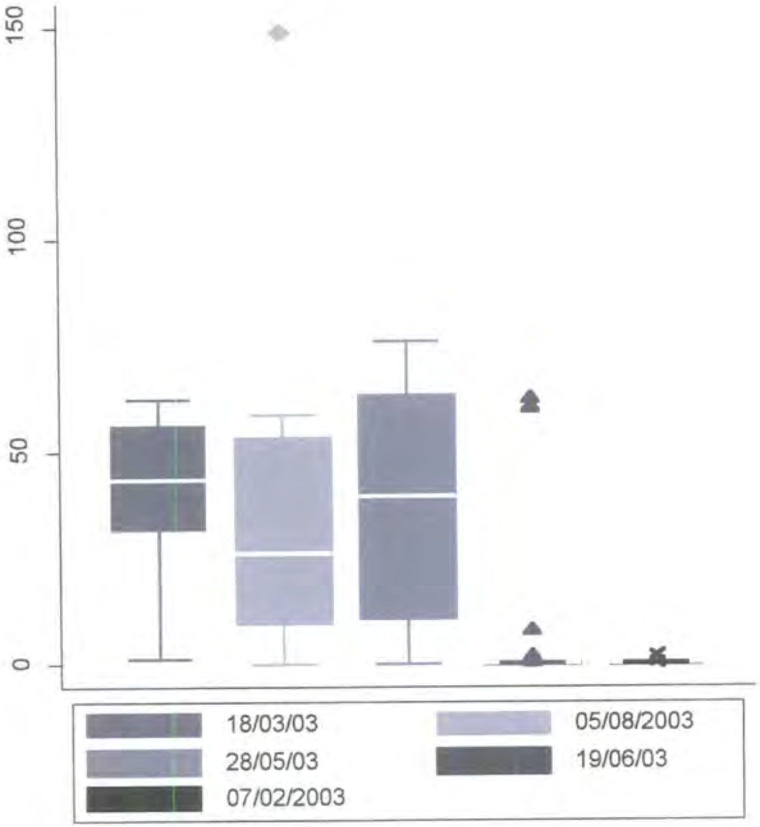


Figure 4.36

Box and Whiskers plots to show the distance that the tracers moved downstream during each event.

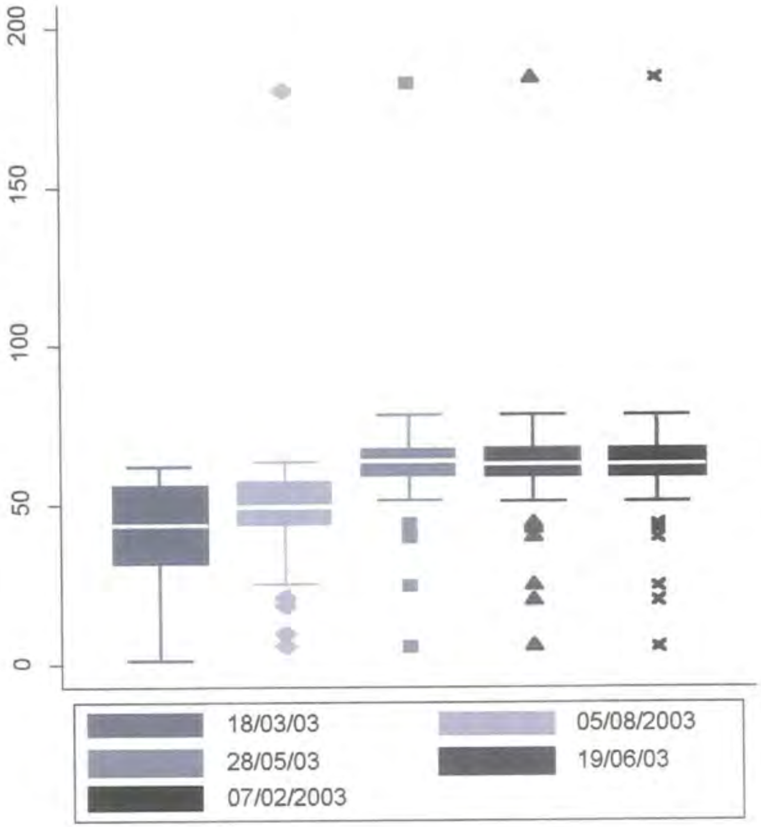
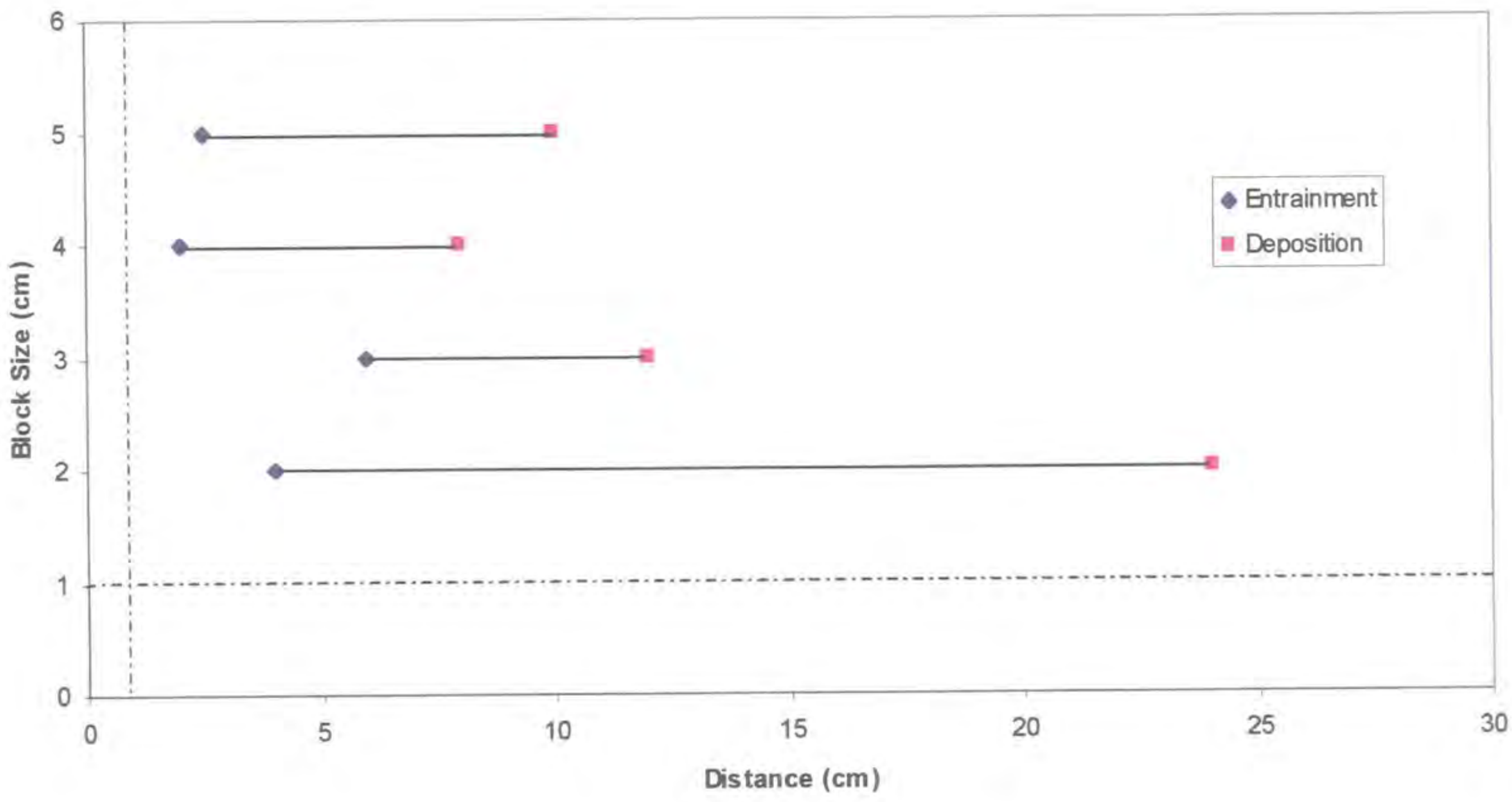


Figure 4.37

Entrainment and deposition values for block sizes next to a bed step.



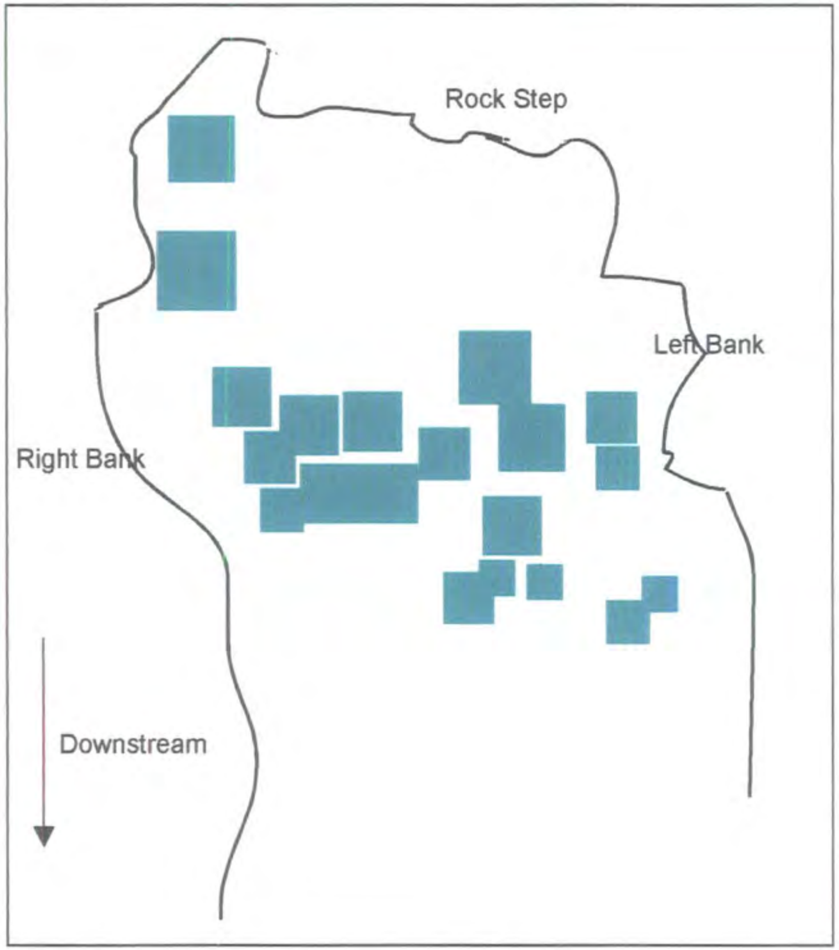
The reason for this is that the blocks were above or at the height of the bedstep, so once the blocks were moved away slightly from the bed step the accelerating flow over the step produced enough force to move each of the blocks. The differences in deposition are due to both block size and weight. Flow over the step accelerates producing an increase in velocity and also an air pocket directly in front of the step. As the block is moved out from the step it exerts a greater influence on the flow until it is positioned in the middle of the main flow from the step. The force changes with the block size with the 2 cm smaller the 3 cm an extension of the step and 4 and 5 above the step. In each case the force is applied to a different area of the block. The increasing block size causes disruption to the flow of the water over the step so the water is no longer able to accelerates over the step.

4.8 Rock step data

Figure 4.38 and 4.39 show the rock step data collected in the field. The basic channel features were mapped and the b axis of each bedrock block was also measured. This data are compared with the bed step data collected from the flume to try and establish a relationship between step height and distance travelled. The data show that the shape of the two bed steps used in the field were very different. Also Figure 4.38 illustrates a band of blocks across the bed with the largest ones nearest to the rock step.

Figure 4.38

Rock step on Trout Beck on the first bedrock section NY 74463 32771



Key

B-axis (mm)

■ 260-350

■ 460-550

■ 660-750

■ 860-950

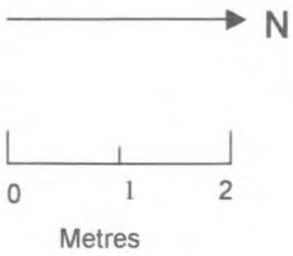


Figure 4.39

Rock step on Trout Beck above the study reach section (Grid Ref: NY 74991 33006)

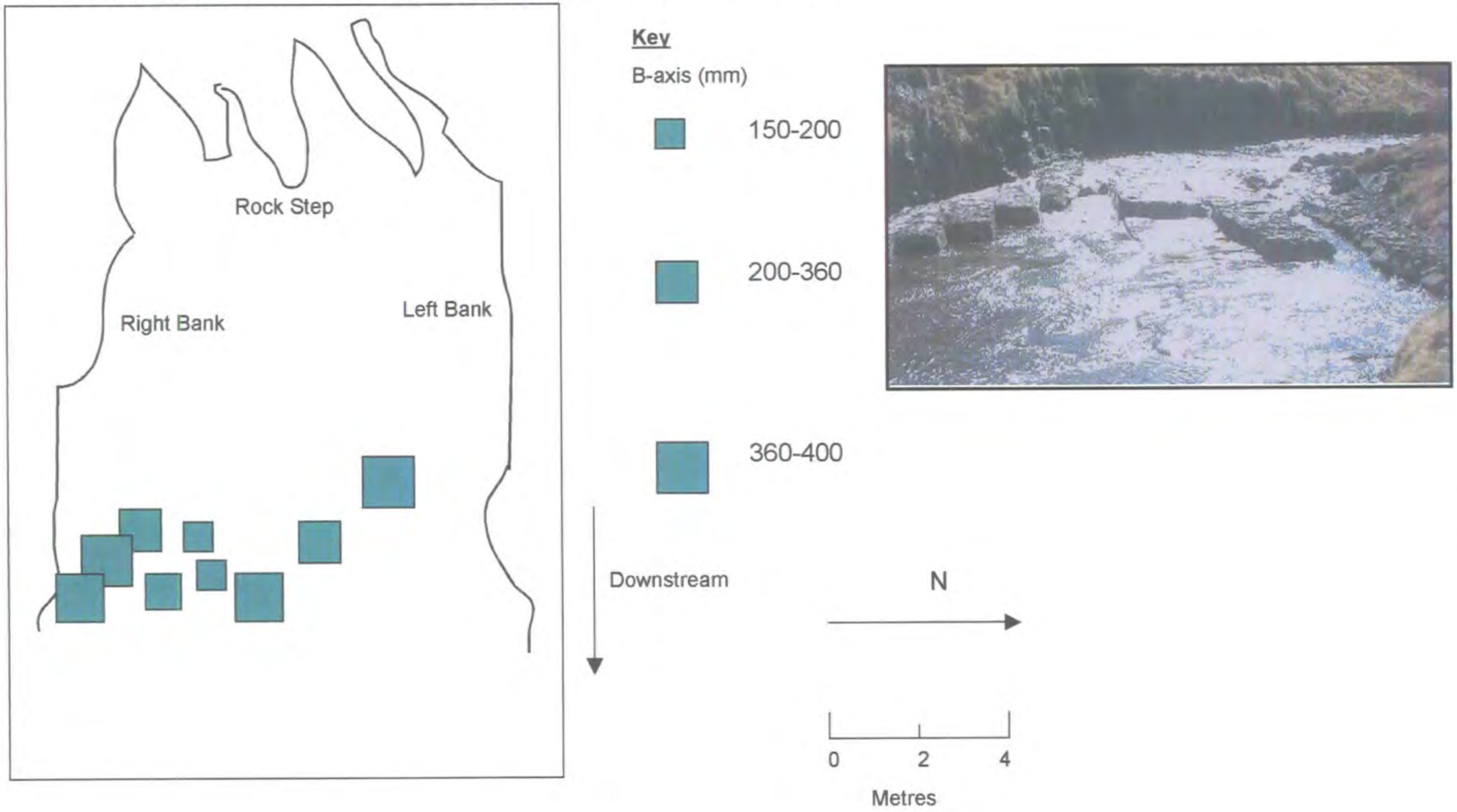


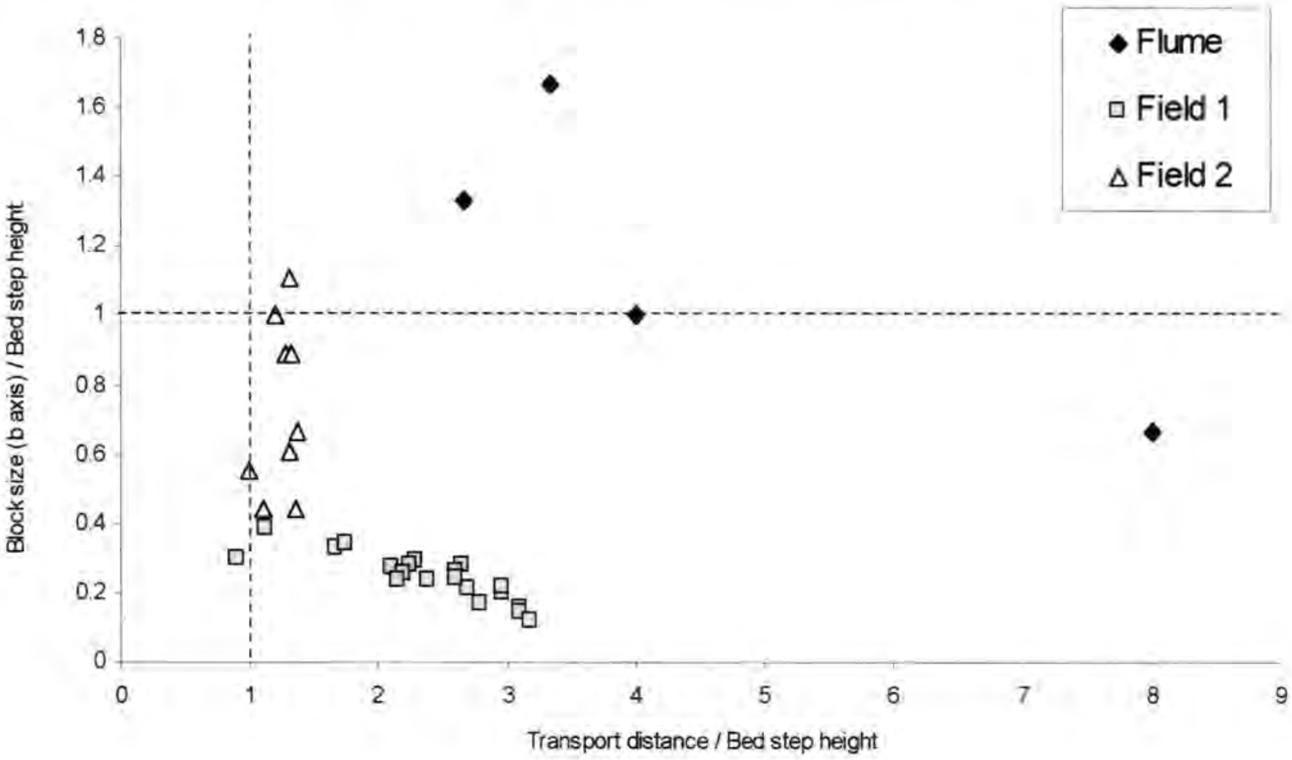
Figure 4.39 illustrates a similar band although much further downstream than in Figure 4.38 and also containing fewer blocks. The reasons for the differences may be due to the variations in step height and also shape. Local hydraulic conditions will also be important in the transportation away form the rock steps. Figure 4.40 shows the ratios of bed step height against distanced moved downstream obtained from the bed step results. The results appear to be highly variable with a large difference between each of the bedsteps. The line on the graph illustrates whether the block is higher than the step. This is not the case in the majority of the field results unlike the results obtained from the flume experiments in which half the results obtained were higher than the bed step. Figure 4.40 highlights the diversity of one type of bedrock landform. In the classification of bedrock channels in chapter five these small landforms were found to have a profound effect on the local hydraulics of the channel and therefore on sedimentation.

4.9 Summary

In this chapter several different mechanisms influence the process of sedimentation in bedrock channels. The tracers experiments have highlighted how sediment travels in bedrock channels and how the erosional landforms produced in bedrock rivers influence local hydraulics which in turn affects how the sediment is transported and also deposited. The different techniques of monitoring sediment dynamics over the study period have illustrated that a combination of techniques is better than a single approach as often one technique may miss an important aspect of change within a reach. The influence of small-scale bedrock features was specifically examined in the flume experiments on rock steps. It was found that rock steps are complex and very diverse which is why they have such an important influence on hydraulic conditions and sediment dynamics in bedrock channels.

Figure 4.40

Bed step data illustrating the ratios between step height and distance of block travelled.



Chapter 5 – Results : Bedrock Stream Classification

5.1 Introduction

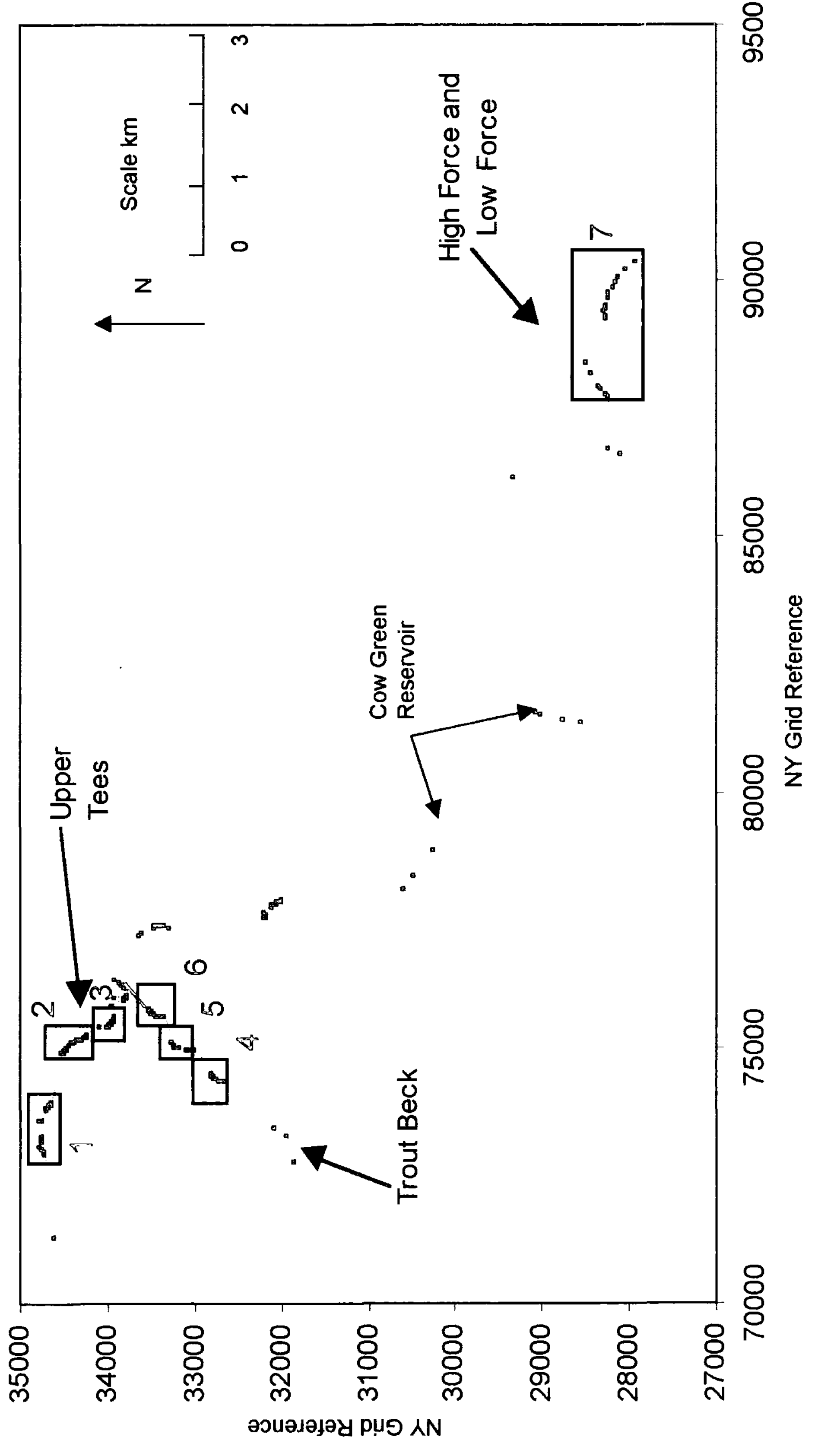
This chapter presents the results of applying the Bedrock Stream Classification scheme proposed in Chapter 3 (Figure, 3.7). An outline of the study area is given and specific bedrock sites on both Trout Beck and the Tees are discussed. The chapter uses Markov chain analysis to examine the transitions between reach classes in the classification scheme. The influence of distance downstream, stream order and the characteristics of the river banks are considered.

5.2 Classification of the Tees and Trout Beck.

Figure 5.1 shows the distribution of transition points obtained from the classification of channel reaches on Trout Beck and the Upper Tees. The clusters of points represent where changes in the bedrock channel classification occur. These particular areas are studied in more detail later in this chapter. Generally where the frequency of transitions is greatest these areas correspond to bedrock sections of the river channel. Areas without transition points are alluvial in nature. It can be observed from Figure 5.1 that the majority of the bedrock sections lie within the upper catchment. Below the confluence of Trout Beck and the Tees the number of bedrock sections appear to be fewer and these also tend to be shorter. This is with the exception of the final section (Section 7) which includes High Force and Low Force and is the largest section of exposed bedrock channel in the study area. The geology of the bedrock sections is dominantly Tyne Bottom Limestone, with the exception of High Force and Low Force which is influenced by the Great Whin Sill

Figure 5.1 Bedrock channel classification .

Transition points on Trout Beck and the Upper Tees. The aeas highlighted by the boxes are bedrock sections each section has a reference number which are discussed in more detail in the chapter.



5.3 Classification of the Tees.

5.3.1 Upper Tees

The Upper Tees section is the first large area of exposed bedrock in the channel system (Figure, 5.1 Section 1). The detailed section (Figure 5.2) shows large areas of bare bedrock in the upper reaches (Figure 5.6) which is followed by a gradual transition from the bare rock to alluvium. The transition includes a long section of river where bedrock is exposed at the margins of the channel or in very small patches just below the sediment surface. In this reach the sections of alluvial channel are long with small intermittent exposures of partially covered bedrock. There appears to be a gradual change through the full range of classes from the initial bedrock section to the downstream alluvial reach. The classification gradually shifts through classes five, four, and three. However the transition through the full classification is not complete and the sequence is ended with an abrupt change from class three to a five (Figure 5.2). The transition from bedrock to alluvial involves most of the classes, however the change in the other direction is not consecutive and jumps occur between classes e.g. 3-5.

5.3.2 Middle Tees

Due to a large number of transitions between classes over a short distance, the main bedrock reach in the middle part of the Tees is divided into two sections (Figure, 5.1, Sections 2 and 3).

Figure 5.2 Bedrock classification of the Upper Tees (Figure 5.1, Section 1)

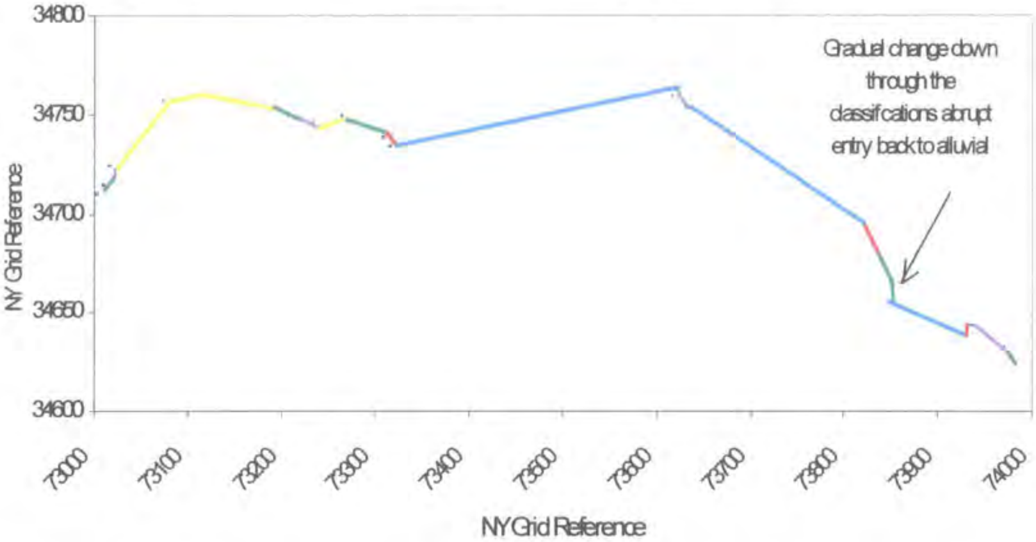
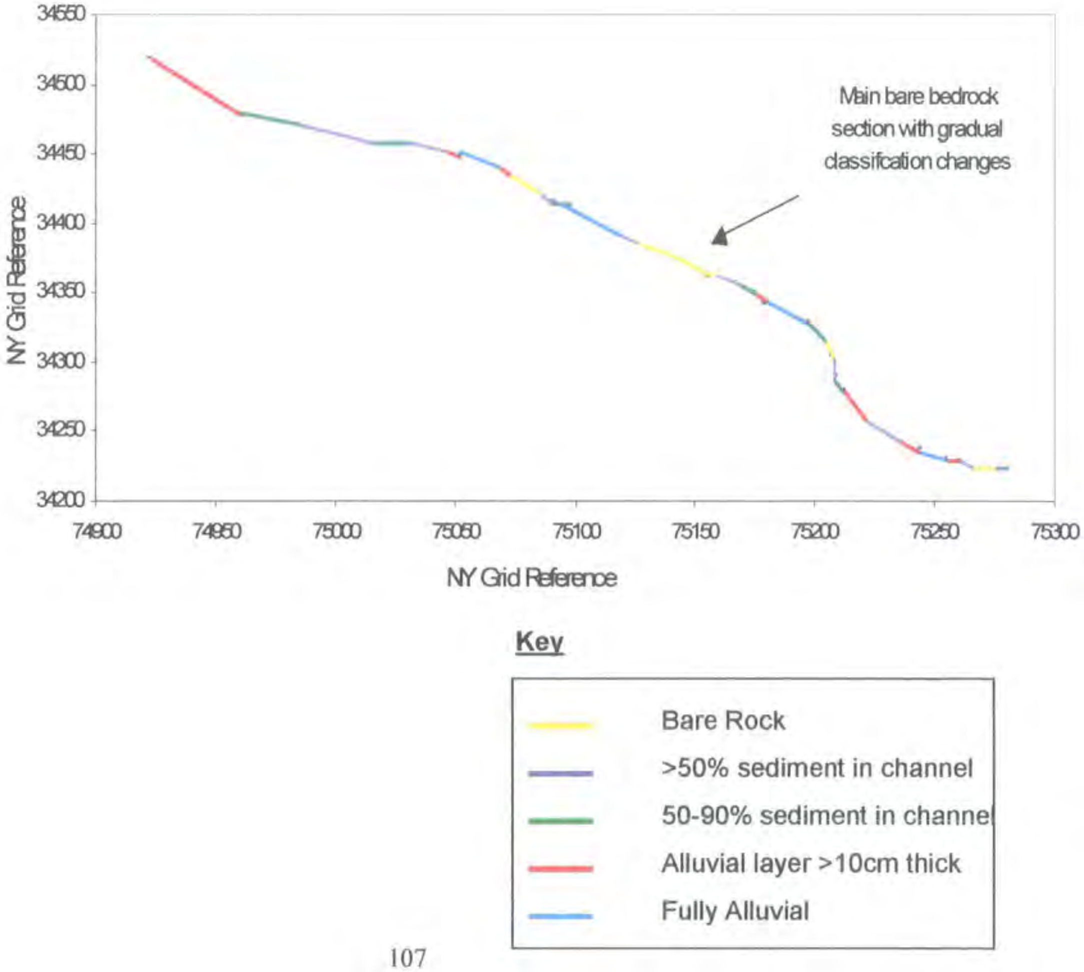


Figure 5.3 Bedrock classification of the upper middle Tees (Figure 5.1, Section 2)



5.3.2.1 Upper Middle Tees (Figure 5.1 Section.2).

The Upper Middle Tees (Figure 5.3) shows multiple transitions over a short distance. These changes in channel classification occur over short distances and do not follow a clear pattern. The channel classes switch abruptly from alluvial to bare rock. However, the largest section of bare bedrock in the reach has a gradual transition in and out with the amount of in-channel sediment varying gradually. The shortness of the sections and rapid transitions suggest that this part of the river is fairly dynamic and local factors control the storage of sediment (Figure, 5.7).

5.3.2.2 Lower Middle Tees (Figure 5.1, Section .3).

The Lower Middle Tees section is very different from the upper one even though they are in close proximity. The section contains longer reaches of similar character and the transitions between classes are gradual (Figure 5.4). In this part of the river there is very little bare bedrock and the section is dominated by bedrock reaches with varying degrees of sedimentation. Within the reach a higher frequency of class four channel is recorded than in many other reaches, however the alluvium is shallow and will be easily redistributed at high flow. Although the length of channel classes two and three are much longer the lack of bare bedrock suggests that in this part of the river more sediment is in storage than in the upper middle reach bedrock section where bedrock is frequently exposed and the occurrence of class two channel is far more frequent (Figure 5.8).

Figure 5.4 Bedrock classification of the lower middle Tees (Figure 5.1, Section 3)

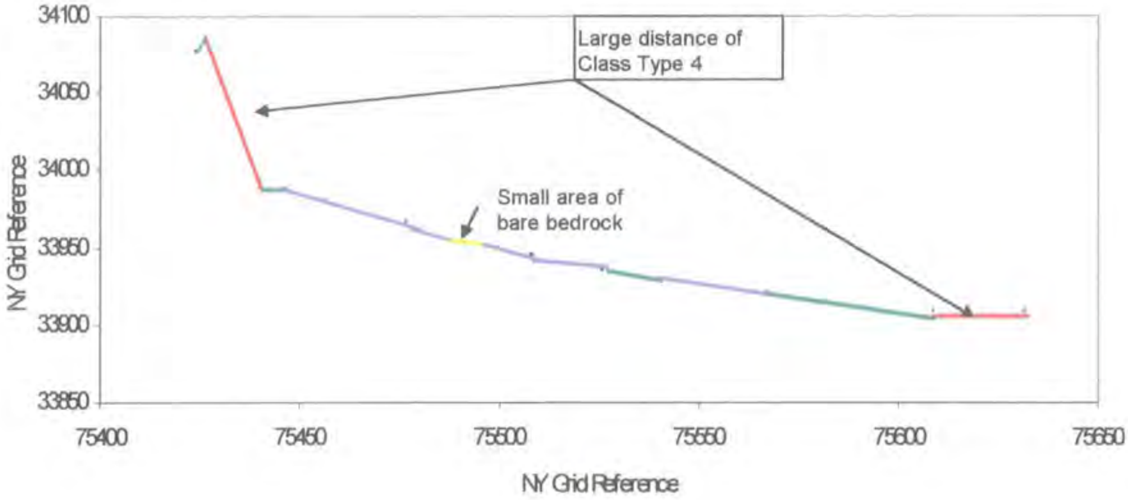
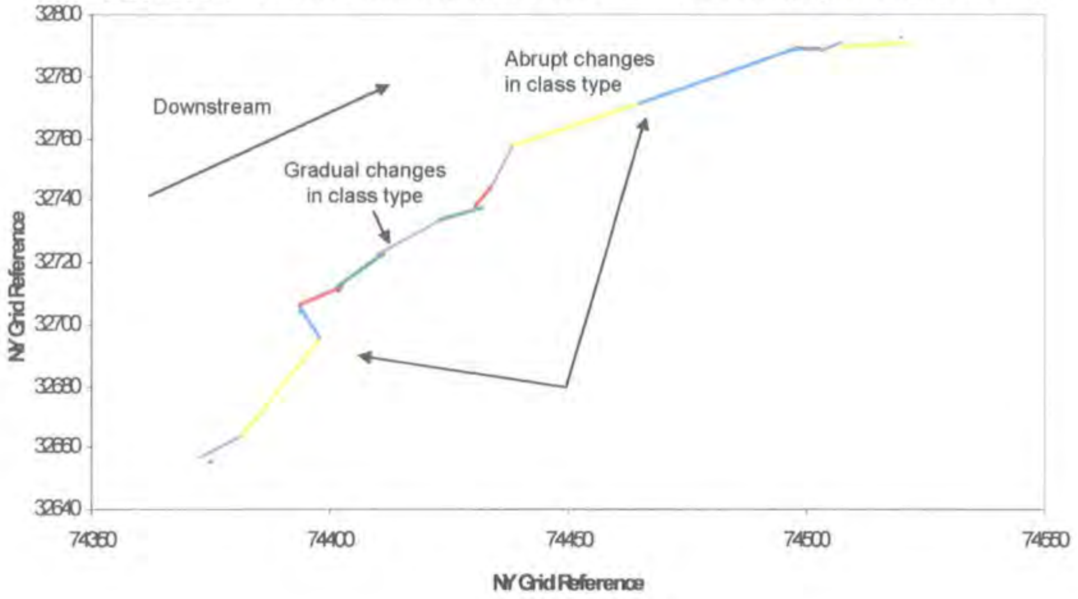


Figure 5.5 Bedrock classification of Section 4 Trout Beck (Figure 5.1, Section 4).



Key

🟨 Bare Rock

🟪 >50% sediment in channel

🟩 50-90% sediment in channel

🟥 Alluvial layer >10cm thick

🟦 Fully Alluvial

Figure 5.6 Bare bedrock channel located in the Upper Tees (NY73150,34750). Classification 1

Figure 5. 7 Gradual transition in bedrock channel sedimentation in the middle of this section on the upper Middle Tees. Class changes from 2-1,1-2,and 2-3. (NY75155, 34352).

Figure 5.8 Sediment on the bedrock channel in the Lower -middle Tees. Class 2.(NY75525, 33943)

5.3.3. Trout Beck (Section 4)

Trout Beck (Section 4) is the first main section of bedrock channel (Figure, 5.1, Section 4, NY74450, 32750) in this part of the river system. The classification of upper Trout Beck shows gradual change through the channel classification system into a bedrock section. The upper section contains three areas of bare rock (Figure, 5.5). The gradual change from alluvial into a bare bedrock is in contrast with the abrupt end to the bare rock sections which immediately become a fully alluvial reach. The classes downstream gradually change from 4, 3, 2, 3, 4, 2, 1 (Figure 5.5 NY74390). However there is an abrupt change after the final class 1 section (Figure 5.5, NY74459). The change is rapid and immediate from one end of the bedrock classification scale to the other. This is due to bare rock sections culminating in large rock steps with deep plunge pools (Figure, 5.12).

5.3.4. Middle Trout Beck

The middle section of Trout Beck contains the main study reach (Figure, 5.1, Section 5). Within this section many characteristic erosional features of bedrock channels can be observed (Figure 5.9). In this section of river a series of short transition reaches were found at the start of the reach, before a long bare bedrock section (Figure, 5.9). There appears to be a gradual change through the classification ending in bare bedrock. A descent through class types from 4-3-2-1 occurs along the study reach. This section experiences a large drop in height over a short distance (Figure, 5.12) which appears to be an important control on sediment movement within the channel.

Figure 5.9 Bedrock classification of middle Trout Beck (Figure 5.1, Section.5)

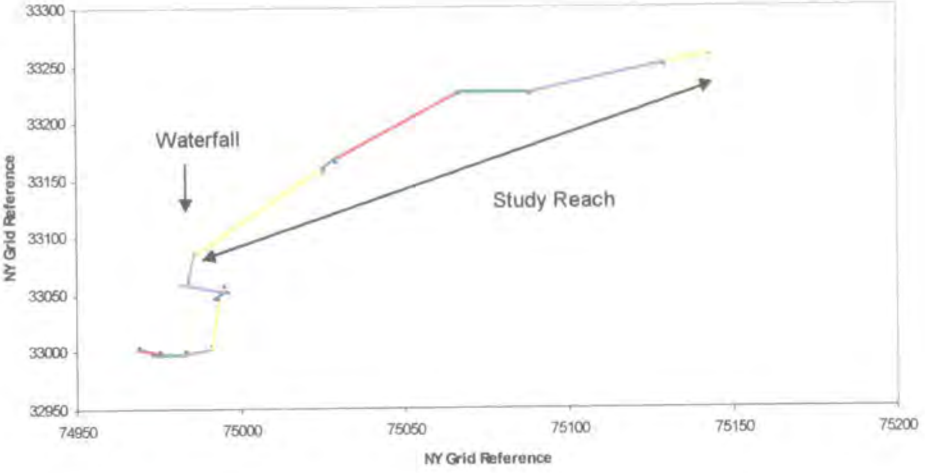
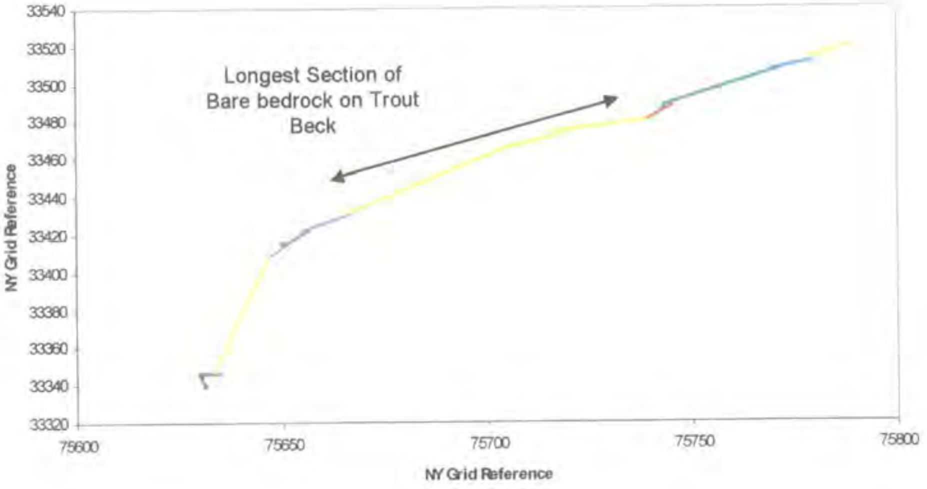


Figure 5.10 Bedrock classification of lower Trout Beck (Figure 5.1, Section .6)



Key

🟨	Bare Rock
🟪	>50% sediment in channel
🟩	50-90% sediment in channel
🟥	Alluvial layer >10cm thick
🟦	Fully Alluvial

5.3.5 Lower Trout Beck

This section of Trout Beck is the last bedrock section before the river joins the Tees (Figure 5.1, no.5). Initially in this section there is an immediate short transition into a long bare bedrock section, which occurs in the middle of the study reach (Figure 5.10). The length of bare bedrock in this section is the longest in the Trout Beck reach. This section contains the largest waterfall on Trout Beck, which provides an excellent example of a knick point (Figure, 5.13). In the upper section the transitions into and out of the bare rock section appear to be gradual. Above the long bedrock reach, the transition changes from 1-2-3-2-1 (NY75468 33425). The narrow gorge after the waterfall contains a large volume of stored sediment. In this section there is a short reach with some alluvium but it is of class type four and would be expected to be mobile under a high flows..

5.3.6 Lower Tees

The lower Tees bedrock reach occurs 19 km downstream of the other main sections of bedrock channel (Figure 5.1, Section7). However it contains the longest stretch of exposed bedrock in the study area (Figure, 5.14). In general a long alluvial reach connects the waterfalls of High and Low Force (Figures, 5.15, 5.16). The transitions between reaches are very abrupt switching from fully exposed bedrock to alluvial sections (Figure, 5.17). There are some smaller sections with a degree of sedimentation (class 2). The sediment appears to be swept from the pools to deposition reaches downstream. In this section the river is either alluvial or contains virtually no sediment. This section is the most unusual and distinctive within the area studied, due to two large waterfalls. The waterfalls cause abrupt changes in sediment transfer which results in large changes in the classification of the channel.

Figure 5.11 Bedrock step on Trout Beck (NY74460,32760)

Rock step

Figure 5.12 Illustration to show the drop in height in the Trout Beck study reach section (NY74988, 33084)

Start of bedrock section

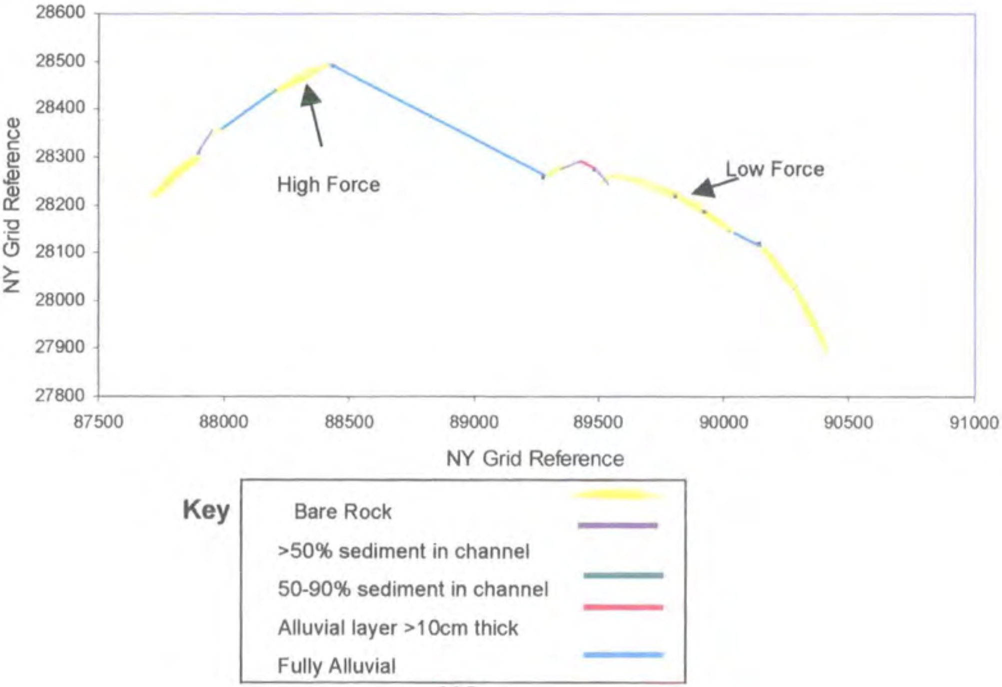
Figure 5.13 Waterfall on the lower Trout Beck bedrock section (NY75749, 33471)

Figure 5.14 Illustration to show the wide expanse over bare bedrock in the lower Tees

Figure 5.15 High Force – Lower Tees

Figure 5.16 Low Force – Lower Tees

Figure 5.17 Bedrock classification of the lower Tees (Figure 5.1, Section .7).



5.4 Analysis of bedrock channel type transitions.

Transitions, from one bedrock class to another differentiate the two main tributaries studied here. These are shown in Figures 5.18 to 5.20. On Trout Beck (Figure 5.18) the gradual transitions appear to be the most frequent (e.g. 1-2-3-4-5) and abrupt transitions such as 5-2 or 4-1 are much rarer. On the Tees there is more variability in the transition sequence. Abrupt transitions such as 4-1 and 5-2, occur more infrequently (Figure, 5.19). On the Tees the most popular transitions seem to be either side of the class type, the next transition either up or down the scheme. For example, 4-3, 4-5 and 4-2. However, as found in Trout Beck the most frequent transitions are again (5-4-3-2-1). The transition of 1-5 being one of the most popular in the Tees as well as in Trout Beck where a bare bedrock channel suddenly, within a few metres, becomes a fully alluvial channel. The Tees data the transition of 5-1 is recorded relatively frequently, however this is a rare transition in Trout Beck and requires a fully alluvial channel over a few metres to change to bare bedrock.

For the river systems as a whole the most frequently occurring transitions tend to be towards the end points (1 and 5) of the classification (Figure 5.20). However there appears to be a relationship between class types 1 and 5 with very high occurrences recorded for such a large difference in sediment within the channel. The most frequent class type transition is from 3-2, this class is primarily bedrock however has a varying degree of sediment

Figure 5.18 Frequency of bedrock channel class transitions in Trout Beck

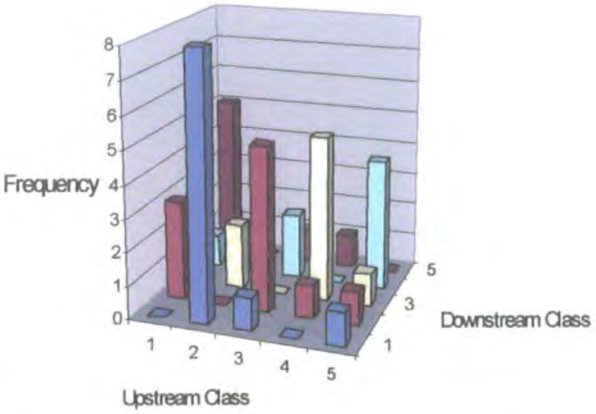


Figure 5.19 Frequency of bedrock channel class transitions in the Tees

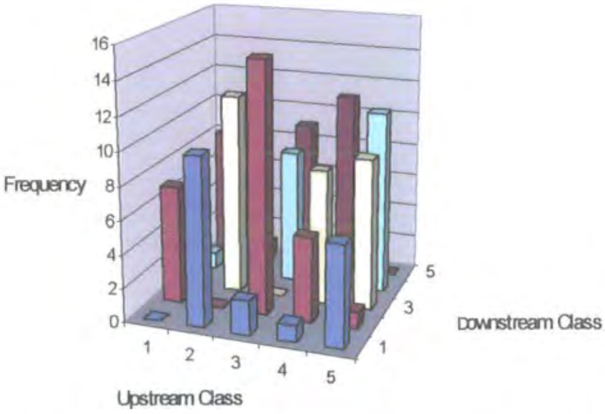
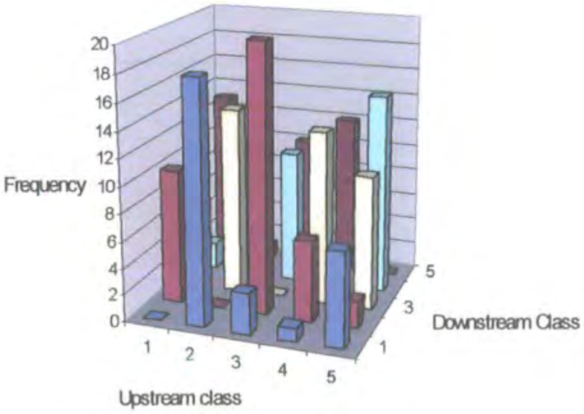


Figure 5.20 Frequency of bedrock channel class transitions for both the Tees and Trout Beck.



Figures 5.21 and 5.22 show the transition type and frequency of each transition type. The most frequently occurring transitions are those that descend through the classification from 5 to 1 e.g (5-4, 4-3, 3-2, 2-1). These sequences represent gradual changes in sedimentation in the channel. The middle class transitions are poorly represented with only low frequencies (1-4, 2-5 ,4-1). Large transitions in class are better represented at a high level as the transition change from 1-5 and 5-1 occur frequently. These class type changes represent very sharp changes in sedimentation over a short distance. The implication of a change from class type 1 (bare bedrock) to class 5 (fully alluvial), involves a significant change in sediment transport dynamics for this transition to occur. In Trout Beck (Figure 5.21) there is a higher occurrence of class transitions which descent gradually from fully alluvial to bare bedrock (5-4-3-2-1). The transition between 3-2 (50-90% alluvial) is the most frequent. However the low occurrence of gradual transitions from bare bedrock to alluvial is accounted for by the high frequency of transition 1-5. In the Tees (Figure 5.22) both the change from alluvial to bedrock and the ascent through the classes from bedrock to alluvial occur with similar frequency. The most common transition is between classes 3-2. A large difference between the Tees and Trout Beck is in the abrupt transitions of 1-5 and 5-1 which occur infrequently in the Tees. This is mainly because of the higher frequencies of gradual transitions (5-4-3-2-1-2-3-4-5) and the generally greater extent of alluvial sediment within this part of the river system.

Figure 5.21 A Sample of transition class types from Trout Beck. The majority of transition types shown illustrate the frequency of changes either side of a class type.

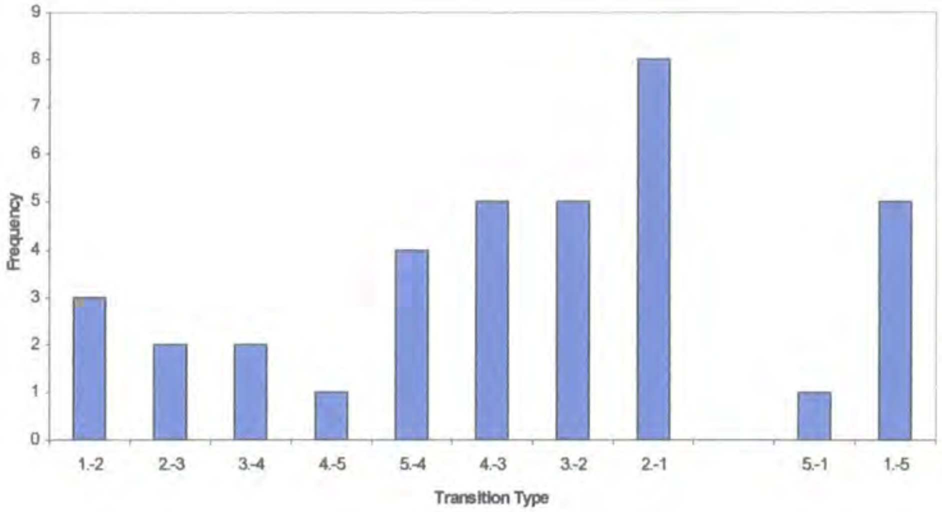
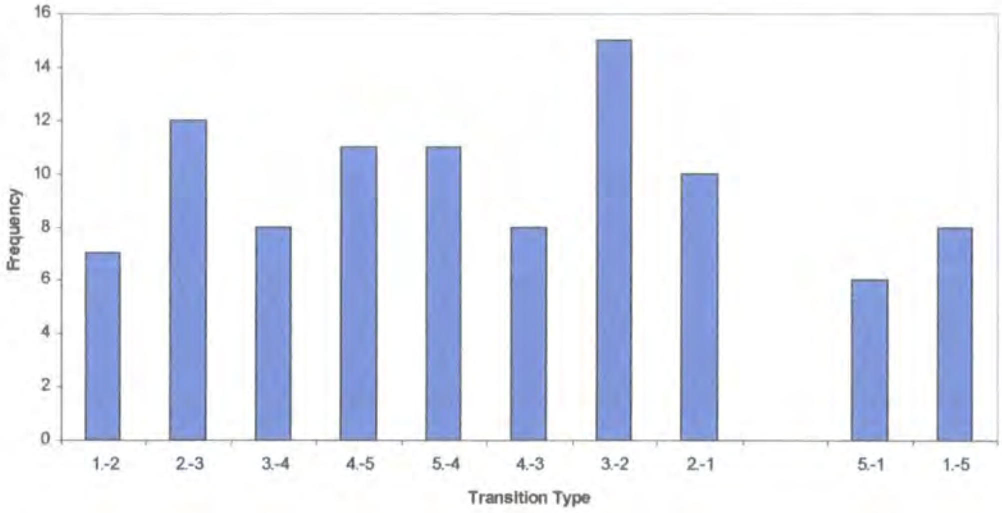


Figure 5.22 Selected transition class types from the Tees. The majority of transition types shown illustrate the frequency of changes either side of a class type.



5.5 Markov chain analysis

Markov chain analysis is a technique which examines structure in sequences of data. The technique is used to assess the probability of transitions from one state or class to another (Davis, 1986). In the present study Markov chain analysis is used to test whether the transitions observed from one type of bedrock channel class to another are statistically significant. The whole data set for both Trout Beck and the Tees is used in the analysis. In this example, transitions from one state to the same state are not permitted and an embedded Markov chain analysis is appropriate. Tables 5.1 and 5.2 show the matrixes produced in different stages of the calculations for the embed Markov chain analysis. Table 5.1 shows the source data used in the calculation that is a compilation of the data collected from Trout Beck and the Tees. Table 5.2 shows results obtained that demonstrate the probability of a transition occurring.

Table 5.1 Source data used for the Markov calculation.

	1	2	3	4	5		**Total**
1	■	18	3	1	7		**29**
2	10	■	20	6	2		**38**
3	6	14	■	13	10		**43**
4	2	5	10	■	15		**32**
5	13	1	10	12	■		**36**
Total	**31**	**38**	**43**	**32**	**34**		**178**

Table 5.2 The transition probability matrix for the changes in bedrock channel state

TO

		1	2	3	4	5
	1		62	10	4	24
FROM	2	26		53	16	5
	3	14	33		30	23
	4	6	16	31		47
	5	36	3	28	33	

The results shown demonstrate the probabilities of the class transitions. The critical value of Chi squared for 11 degrees of freedom at the 95% significance level is 19/675. Using Chi squared the most significant transitions are 1-2, 1-5, 2-1, 2-3, 3-2, 3-4, 3-5, 4-3, 4-5, 5-1, 5-3, and 5-4. During the analysis of the transitions these were also found to be the most frequent. The test statistic exceeds the critical value therefore successive bedrock channel classes are not independent but show a strong first-order Markovian property. The highest probability of channel occurrence is the transition from 1-21 a 62 % chance of the transition occurring in the channel. Also included in Table 5.2 are the transitions between 1-5 and 5-1 which have a probability of 24 % and 36 %. The probabilities obtained from the Markov analysis confirm the results displayed in Figure 5.21 and 5.22 which show that transitions are likely to change by one class either side of the original class, i.e. 4-3 or 4-5. The results show that often abrupt changes occur at the ends of bedrock and alluvial reaches as seen in Trout Beck.

5.6 Distribution of class reach lengths

Table 5.3 Proportion and length of different bedrock channel classes in the Trout Beck and Upper Tees streams.

Classification no.		Tees (m)	%	TB (m)	%	Total (m)
1	Bare Rock	2053	10	272	5	2325
2	< 50%	619	3	158	3	777
3	51-90%	584	3	364	8	948
4	Sediment mobile	558	3	103	2	661
5	Alluvial	16339	81	4031	82	20370
	Total	20153		4928		25081

Table 5.3 shows that the majority of the channel was classified as alluvial (81 %). It is significant however that 19% of the channel is dominated by bedrock forms that are approximately a 1/5th of all the river channel surveyed. Both in the Tees and Trout Beck bedrock channel classes two (>50% sediment) and four (>10 cm alluvial) occur the least. In the Tees the total of bare bedrock is much higher (10 %) to that found on Trout Beck (5 %). As can be seen from Table 5.3 there is a large difference in the proportion of class three channel (50-90% sedimentation) in the two river systems. In Trout Beck the frequency of this class is nearly three times greater than in the Tees. This may be due to cyclic nature of sediment within the gorge or narrow river channel sections. Trout Beck is smaller and more confined than the Tees; sediment accumulates quickly in suitable areas. However the sediments are just as easily washed away as the bedrock enables the sediment to be more mobile (lower bed roughness and resistance). On the Tees there are fewer gorges and bed rock step sections which suggest that sediment transfer is less interrupted. However in terms of channel length bedrock features maybe relatively minor but the effect upon the river system can still be profound e.g High Force. The bedrock sections studied on Trout Beck have a stream order of 4 for the two upper sections and 5 for the final section.

On the Tees a similar pattern occurs the first three sections (1,2,3) occur on a river stretch where the stream order is 4 the final section occurs on a river where the stream order is 5. Stream order is significant because the higher the stream order the larger the river capacity is to both move sediment and also acquire sediment. Trout Beck although a lot shorter in length than the Tees has a similar stream order, therefore suggesting that the ability of the flow to move sediment should be similar.

5.7 Lengths of bank classes in Trout Beck and the Tees

Table 5.4 Total distances of the different bank side types in Trout Beck and the Tees.

Bank Classification		TB (m)	%	Tees (m)	%	Total (m)
Both Bedrock	BB	353.5	7	1032	5	1385.5
Left Bedrock, Right Alluvial	BA	16	0.003	564	3	580
Left Alluvial, Right Bedrock	AB	137	2.997	130	1	267
Both alluvial	AA	4421.5	90	18427	91	22848.5

The Table 5.4 shows that 90 % of the bank type along the full distance of channel classified in both rivers is alluvial on both banks. Both the rivers have a low percentage of channel where bare rock occurs on both sides (7% and 5%). It appears that alternating bedrock and alluvium banks are infrequent within these river channels. A much larger percentage of the channel has alluvium banks than was classified as fully alluvial in the channel bed survey (Table 5.5). Very infrequently do bedrock banks and bed occur together creating a gorge section (Table 5.3 and Table 5.4). Also bedrock banks and an alluvial bed are rare as gorges tend to be efficient areas of bedload transport. Table 5.6 also implies because 20% of bed is bedrock (Table 5.3) but only 7-10% of bank is bedrock, that there is a large sections of channel which have a plane bed (Figure 2.5).

5.8 Summary

In this chapter the distribution of bedrock within the upper Tees has been quantified Figure 5.1 shows the variety of bedrock forms and changes which occur on the Tees and Trout Beck. In the seven sections analysed in detail a variety of different patterns of channel form have emerged. No section was the same in terms of lengths of bedrock channel classes or the style of transitions. However, the analysis of the transitions demonstrated some common channel class changes. It was found that a change form alluvial to bedrock occurred gradually going through a series of classes (5-4-3-2-1). This occurred on both rivers but was more common on the Tees than Trout Beck. Also abrupt changes occurred at the end of alluvial reaches and the beginning of bedrock sections (1-5-1), this was more common on Trout Beck. The analysis of channel as a whole showed that 20% of the upper Tees reaches had significant bedrock control. However only 10% of the upper Tees had bedrock banks which suggest that large areas of the river channel have a bedrock bed but alluvial banks.

Chapter 6 - Discussion

6.1 Introduction.

This chapter discusses the main results of the thesis. This includes discussion of the results obtained from the re-sedimentation study of the bedrock channel reach on Trout Beck; data from the flume experiments and field observations related to the main field studies; and finally the implications of the results from classification of the bedrock channel at the river basin scale.

6.2 Sedimentation at the reach scale.

Sedimentation in the bedrock study reach was surveyed at a variety of scales using fixed point photography, cross sections, geomorphic mapping and sediment analysis of selected areas of the channel bed. Through these methods it was found that from 11/11/02 until 3/7/03, there was a 5 % increase in the area of sedimentation in the channel. At the beginning of the study following the flood event in July 2002, bedrock was visible throughout the entire reach, however over the study period resedimentation had occurred in selected parts of the channel.

Upstream of the bedrock reach recent channel adjustment in an alluvial reach provided a large supply of sediment from a bar complex which was substantially increased during the flood in July 2002. The supply of sediment from upstream contributed small areas of sedimentation in the upper sections of the bedrock reach. Sedimentation also occurred just before the narrow bedrock gorge section (Cross-section 5, Figure 4.22) in the area where the tracers were seeded into the bed. Evidence from fixed point photography and geomorphic mapping suggests that the bar formed in this area is a fairly ephemeral feature. This may be due to a large boulder which obstructs the channel at low flows and causes a local build up of sediment.

At high flows the sediment is able to move above and around the boulder thus leading to a cyclical process of sedimentation and erosion dependent on fluctuations in the discharge of the river.

The narrow bedrock gorge section (Cross sections 5-12, Figure 3.3) which contains several bedrock step-pool sequences showed only minor sedimentation when compared to the rest of the study reach. This part of the reach appears as a high gradient cascade on the long profile of the study reach (Figure 4.1). Cascades are usually characterised by a tumbling flow and lack signs of channel sediment storage. Rapid scour of bed material during high flows means sediment deposition is limited under cascade conditions (Kondolf *et al.*, 1991). Sediment stored in this section mainly occurred just before a step or within pool sections, there is little evidence of lateral sorting. Montgomery and Buffington (1997) suggest that changes in flow (gradient) are frequent within step-pool sequences. They also state that primary flow and bed fluctuations appear to be vertical rather than lateral.

The narrow gorge ends in a section which contains a number of bars. These small bars, over the course of the study period amalgamated to form a larger sedimentation zone. Sediment was initially stored behind a large boulder which appears to restrict the sediment movement through this section. Elongate bars are formed in areas of local flow expansion along valley margins (Cenderelli and Cluer, 1998). The flow is slower along channel margins where the main concentration of the flow is usually absent in bedrock rivers. Expansion downstream of a constricted small reach such as a narrow bedrock gorge allows for sedimentation to occur. Multiple bars tend to amalgamate and are separated by minor shallow channels (Cenderelli and Cluer, 1998).

The main concentration of sedimentation in this area occurs at the end of the bedrock gorge where the river widens and flow velocity is reduced, resulting in sediment being deposited. Bisson *et al.* (1982) and Grant *et al.* (1990) suggest that adjacent reaches often exert very different flow conditions dependent on the hydraulic radius of the channel. In the gorge section the hydraulic radius of the channel is significantly smaller than in the lower plateaux section of the study reach. Therefore the flow characteristics of the reach are dependent on the gradient and also the degree of lateral confinement of the channel. The large rock step complex (Figure 5.9) on Trout Beck at the start of the study is suited to sediment storage. Fixed point photography of this area shows changes to the sediment bars over time which under go erosion and deposition, although the overall trend is one or increasing sedimentation. Despite slow rates of morphological change bedrock systems tend to acrue change over time (Tinkler and Wohl, 1998).

At approximately 200 m downstream, the study reach flattens out on to a bedrock bed which has undergone gradual sedimentation throughout the year. This area has a low gradient and is best described as a plane-bed channel (Wohl, 2000). The area of the channel often contains ephemeral fine-grained sediments which appear and disappear frequently after flood events. Clasts sizes greater than 100 mm were largely absent in the deposited sediment. The study reach ends with an abrupt change from a bedrock channel with a plane bed to a fully alluvial reach. Over the study period sediment accumulated on the lower part of the bedrock section with sedimentation occurring initially along the margins of the channel but slowly moving inwards from both banks to form a fully covered alluvial bed (Figure 4.22).

The increase in sedimentation within the channel is also supported by evidence from selected sediment transects surveyed to determine changes in sediment size over the observation period. The sediment deposited showed changes in the size of clast sizes particularly 128-210mm and also 64-128mm size range. However, the resurvey found virtually no change in the very large sediment (>2000 mm). The resurveys of the channel on selected cross sections supported the hypothesis of gradual resedimentation of the river bed. The results obtained illustrate an increase in coarse sediment deposition suggesting this sediment was deposited in the channel during larger flow events. The discharge record obtained from the state logger shows four significantly large flow events, two of which produced significant movements in the tracers. There was also a notable reduction in the amount of fine sediment in the 5-20 mm Tinkler and Wohl (1998) state that bedrock rivers are often coarse in clast size 100-2000 mm and a lack an appreciable fine sediment population.

The sediment analysis of the bars showed that larger clast sizes were more common in the middle of the bar and smaller clast sizes were frequently found around the edges of the bar (Figures 4.24,5,6). The two bars surveyed were quite stable and the tracers deposited on these bars were approximately the same size as the sediment found on the bar surface. These were present on 11/11/02 when the original geomorphic mapping survey was undertaken. Following the July 30th 2002 flood the channel was completely stripped of all bars. The sediment bars below the gorge section of the reach which were surveyed have gradually build up over the study period. The bars often focus around one or two small boulders or a sheltered area in the bed which provide the conditions for initiation bar growth.

The long-term stability of the bars appears to be due to a core of larger boulder sediment (> 1000 mm) stored in the middle of the bar. This material is stable in higher flows however smaller clasts sizes (< 100 mm) on the edges of the bars are frequently renewed and reworked in lower flows.

The large spatial variation in the character of bed material sediment in bedrock channels reflects the controls on the channel such as geology, lithology, bed structure and also hydraulic change (Miller, 1991b). The tracers which were prepared for the study approximate the medium clast size found on the bar surfaces. The extremes of the distribution, very small and very large sizes were not represented in the tracers (Figure 4.23). The tracer study demonstrated that both local hydraulic conditions and bed structure were important in controlling the movement of sediment through the reach. The tracers where originally placed on a bar at the top of the narrow gorge section. The tracers demonstrated that when discharge rises the majority of the sediments moves quickly through the narrow gorge section (Figure 4.22). Tracers are mainly deposited in large step-pool sequences, at the end of the gorge section where two large bars have formed (Figure 4.22). The majority of the tracers (58 %) are contained within this large step-pool sequence. In general the long profile demonstrates that in the vicinity of the cascade / step-pool sequence the initial high gradient channel slowly changes to a plane–bed reach as the gradient decreases and the number of step-pools is less. Tinkler and Wohl (1998) suggest a positive relationship exits between channel gradient and pool depth. It appears that the higher the gradient the deeper the pool. The long profile of the study reach shows that the deepest step-pool sequences have the highest gradient.

Tracer movement is therefore influenced by the presence of step-pool bedforms and changes in gradient. Depth and velocity increase in the narrow section of channel and increase tracer movement. Tinkler and Wohl (1998) state that within the fluvial system gradient is the most important influence over sediment transport. They suggest that transport reaches are commonly restricted to zones of smooth boundaries and steep gradients such as the narrow gorges (similar to the upper part of the study reach).

In total, five periods of tracer movement were recorded. However there was only significant movement in three of these. In these events the sediment appears to have moved in a slug like form with clusters of sediment forming at approximately 40m, 60m and 80m downstream in the three events respectively. Hoey (1992), suggests that sediment in bedrock channels moves episodically along the channel reach. Very few tracers travelled independently of the main tracer mass. One exception is a clast which travelled 186 m (26/4/03). The majority of tracers were deposited in clusters. In event 4 and event 5 (Figures 4.32 and 4.33), tracers accumulated in a large pool at the end of the narrow gorge section of the study reach (Section 12-13) 69 m downstream of the initial start point.

All the tracers appeared to have travelled completely through the narrow gorge section during high flow, which would have acted as a cascade due to the high gradient. The step-pool sequence in the gorge section would have had a small impact on deposition because the increased depth of flow would drown out the local bedforms. A few tracers were recorded in the gorge section but they occurred in small clusters of one or two particles in small potholes on the bed or in small step-pool sequences both before the step and in the pools.

The long profile picks out the step-pool sequence in the gorge but more noticeably the large step-pool sequence at the end of the gorge (Figure 4.1). At this point in the reach the channel undergoes significant sedimentation. This is due to a combination of change in the flow and also feedback (sediment stacking) from the sedimentation zone downstream.

Tracer movements show large variation in the range and the upper and lower quartiles especially in the first two tracers events (Figures 4.35.36). Over time the range and also the upper and lower quartiles becoming closer to the mean. This suggests that the sediment in each of the tracer events is moving together over a short distance. The final tracer movement events show little variation and the bulk of sediment appears to be stationary in the large pool. This is due to the lack of movement recorded in events 4 and 5 because the tracers are trapped within a large pool. The tracer study also showed that under a moderately high flow (0.6 m flow depth) a boulder with a b-axis of 650 mm travelled 57.8 m. This supports the theory that larger sediment in bedrock channels may move not only in flood conditions but also under less extreme high flow conditions.

Bed step data collected in the field was compared with a simulation experiment ran in the flume. Data were obtained from three rock steps on Trout Beck. The three rock steps were very different in height, angle to the flow and width (Figures 4.38,39). The data show three very different relationships between distance the block moved away for the step and step dimensions (Figure 4.40). This data are limited due to the small size of the data set and also the wide differences between the height and also width of the rock steps.

Out of the three steps surveyed in the field only two were found to have blocks downstream which could be traced to the step. Two of the data sets show data which is roughly clustered however one data set is not (Figure 4.40). The flume data produced a much steeper relationship than any of the other data sets. However the boulders measured in the field may not all have been originally derived from the step. At high discharge many boulders may have over-passed the step from upstream and become deposited much further downstream.

This information of course is absent from the study because no previous survey of the rock steps on Trout Beck had been undertaken. The largest differences in this data may be due to the high variability within rock steps. For the three steps surveyed in the field there were significant differences in shape, height and also angle of the rock steps to the flow (Figures 4.38.39). It is often difficult to compare field and flume studies because of the different techniques used to measure the same variables (Komar, 1987), however in this case similar techniques were applied in measuring distance moved downstream and also on the height of the rock step.

The flume experiments show an interesting relationship between of the size of the rock step and block entrainment. Initially the distance moved is large for the small size block. However this relationship changes when the block size is a similar size to the step (3 cm). It appears that a block size of 4 cm is transported the least distance and is deposited closest to the step after the initial movement. The 5 cm block is entrained at the same point as the 4 cm block but is deposited at a longer distance away from the step. This is despite the block being considerably larger than the 4 cm block.

The majority of the blocks appear to be entrained at a similar point away from the bed step, between 2 and 3 cm, and the distance of movement appears to be large dependent on the height of the block and also the size (weight) of the block. The height of the block is important because the smaller the block the more influence the bed step has over the movement of the block. The step will initially dwarf a small block however when moved away from the step the block will be subjected to full force of the flow. A smaller size block, which is sheltered by the step, will initially not be in the nappe of flow over the step. Gradually as the block is moved out the block enters the nappe of the step and is entrained. With a larger block the flow off the step immediately effects the block, however even with a large block a gap is still required between the step and the block for entrainment to occur. If the block is placed directly next to the step it acts as an extension to the step or is sheltered by the step. When an obstacle is placed in the flume it was found that water flows around the object at an increased velocity (Wohl, 2000). Flow resistance occurs on the bed and also the sides of the flume as described by (Griffths, 1987). Webber (1965) suggests that flow accelerates over an object and a step causing a nappe to occur the flow accelerates off the step due to the force of gravity. This nappe is the point at which the blocks become entrained in the experiments it was found to be approximately 2 cm away from the step depending on block size. Often behind an object an air pocket is established, the small 2 cm block was situated within the air pocket when it was placed directly adjacent to the step. The air pocket if not replenished creates a vacuum and may increase instability through greater local turbulence.

There are complex interactions between hydraulics, sedimentology and grain characteristics which make it hard to define bedload transport rates and equations. It is possible to define reasonable bedload transport equations for alluvial rivers, however less is known about sediment transport in bedrock rivers. Bedrock rivers tend to be flashy in nature and strong gradient control (Tinlker and Wohl, 1998). The difference in gradient and also geology influences the hydraulics and sedimentology of the channel. Gradient is a very important variable for the movement of sediment and local flow hydraulics in bedrock channels (Howard, 1980). In this study gradient had a profound effect on the tracer movements and resedimentation of the channel. The overall gradient of the channel was not always constant and this variability had effects on the local hydraulics and therefore on sedimentation. In areas of steep gradient flows were rapid and sedimentation low, an example being the cascade sections.

The hydraulics channel, in particular the width and also the gradient, exert strong local controls on processes occurring within the channel. Sedimentlogy within bedrock channels again appears to be controlled by specific local conditions such as gradient, sediment supply and erosional landforms which are change frequently due to the variability of discharge.

Further research is needed in to mapping and tracing sediment movement in bedrock channels. Little is known about how sediment moves within bedrock channels and this study has highlighted the complexity of the relationships that exist between different variables. A further survey of rock step sequences would allow a more accurate analysis of the movement of blocks away from rock steps in terms of distance and block size.

Further experimentation in the flume altering the angle of the bed step in relationship to the flow would be useful. As seen in the field, rock steps rarely have a step front orthogonal to the flow. Normally the rock step usually occurs at an angle. Establishing the influence of his angle on flow and movement of blocks away from the step would be useful.

6.3 Classification of bedrock river channels on a basin scale.

Classifications of bedrock channel morphology at the basin scale have been rarely attempted. Channels in bedrock rivers are usually classified at a reach scale (Wohl, 2000). The main aim of the classification used here was to determine the degree of sedimentation in the channel and assess the significance of bedrock channels within the river system as a whole. The classification illustrates five different categories characteristic of UK upland bedrock river channels, representing different degrees of sedimentation. Results showed (Table 5.5) that 20% of the river channel in the Trout Beck and Upper Tees area was classified as containing significant bedrock characteristics. In Britain there has been little research on bedrock channels. One notable exception is the study by Carling (1995) on bedrock hydraulic jumps on Birk Beck a tributary of the River Lune in Cumbria. This is surprising given the trend of increasing research on bedrock channels over the last ten years in many countries such as Australia and U.S.A (Tinkler and Wohl, 1998). Furthermore Montgomery *et al.* (1995) recognise that bedrock rivers are more common than generally thought, especially in both upland and lowland areas.

Within both the Tees and Trout Beck there appears to be frequently occurring stretches of bedrock especially in the headwaters of the basin. Figure 5.1 shows the distribution of bedrock channel features, the majority of which are found above 530 m.

The overall changes in classification within the Tees can be characterised as a decrease in the exposure of bare bedrock from the source to Low Force, with intervening alluvial sections becoming longer and better developed (Figure 5.1). The absence of bare bedrock in the Tees is very notable for a 7.5 km stretch after Cow Green reservoir ending just before High Force. The importance of reach-scale river dynamics within this river, play an important role in the characteristics of the channel. The occurrence of bedrock features on the Tees seems to be controlled by the geology and also the gradient of the river.

Analysis of the transitions between the different classes of bedrock channel showed that there was a high probability of a gradual descent through the classification sequence 5-4-3-2-1 (Figure 5.21). However a gradual ascent was less likely 1-2-3-4-5 due to the levels of resedimentation, sediment tends to move through the channel sporadically. In the present study Markov chain analysis was used to test whether the transitions observed from one type of bedrock channel class to another are statistically significant. The whole data set for both Trout Beck and the Tees was used in the analysis. The probabilities obtained from the Markov analysis confirm the results displayed in Figure 5.21 and 5.22 which show that transitions are likely to change by one class either side of the original class, i.e. 4-3 or 4-5. The results of the Markov chain analysis demonstrates that there is a high probability of abrupt changes between fully alluvial (5) and bare bedrock (1). The results show that often-abrupt changes occur at the ends of bedrock and alluvial reaches as seen in Trout Beck. The transition results overall show that in bedrock channel sections there appears to be a gradual change from alluvial to bare rock and vice versa.

However the Markov analysis noted the high frequency of end transitions 1-5 or 5-1, these may occur more due to morphological controls of the channel than sedimentation controls.

The occurrence of channels within the study areas is approximately 20% of the channel length. However there is a much higher percentage of bare bedrock (10%) on the Tees than recorded on Trout Beck (5%). Trout Beck is smaller and more confined than the Tees and sediment supplied from adjacent slopes accumulates in suitable areas of deposition. On the Tees the channel is less well coupled to side slopes in the upper reaches and lower down the system large scale channel bedrock features occur e.g High Force.

Channel bank types in both rivers are dominantly alluvial (90 %) . Both Trout Beck and the Tees have similar channel lengths with bare rock on both sides (7% and 5%) respectively. Alternating bedrock and alluvium banks are infrequent. And bedrock banks are less significant than bedrock beds in these channels. For example 20% of bed is bedrock (Table 5.5) but only 7-10% of bank is bedrock (large sections of channel have a plane bed) (Figure 2.5). The plane bed sections are often narrow and hydraulically controlled by the bed and also the gradient of the stream. The importance of the bank sides in bedrock rivers is often over looked because the bed is a large control however the banks also have a significant influence over fluvial hydrology (.Tinkler and Wohl 1998).

Bedrock channels remain free of sediment due to the steep stream bed gradient typically found in upland mountainous regions (Howard, 1980). The difference between the bare bedrock sections on Trout Beck and the Tees is mainly due to the local gradient with smaller sections of bare bedrock occurring in the upper Tees and longer sections of bare bedrock on the steeper Trout Beck channel. The long profile sections are controlled by erosional landform such as a rock step or a knickpoints. Howard (1998) suggests that bedrock channels contribute to the flashy nature of the catchment and therefore have a significant role in sediment transport. These bedforms are less frequent in the upper Tees. However in the Lower Tees channel form significantly controlled by High Force and Low Force, which area two major bedrock channel reaches.

The bedrock channel classification proposed here allows the distribution of bedrock and alluvial sections to be characterised. Wohl, (2000) notes that significant differences in sediment transport in bedrock and alluvial channels exist, which influences the rate and patterns of channel change. The morphology of a bedrock channel is the product of the relationship between the fluvial forces and the bedrock resistance (Tinkler and Wohl, 1998). Each bedrock reach will have a particular set of geological or topological controls that influence the sediment transport through each section. Large spatial variability in channel morphology reflects these controls and spatial difference in hydraulic forces (Tinkler and Wohl, 1998). Wohl *et al.* (1994) note that there is a minimal difference between downstream energy expenditure between alluvial and bedrock reaches. Differences in the form of bedrock reaches show how a rock step or a knickpoint can change sedimentation within the channel through changes in the flow.

Tributaries may influence the sediment transport of a reach significantly and have an effect downstream. Kiefer (1988, 1989) suggest that tributaries input coarse material, however in Trout Beck there appears to be little evidence of this. This is probably because adjoining tributaries are also bedrock and have low sediment yields therefore transitions between channels are not only very abrupt. Also sediment transport regime is generally low and does not differs greatly through the stream network.

The bedrock channel classification proposed here should be extended to include the surrounding tributaries of Trout Beck and the Tees. This may alter the overall proportions of bedrock channel in the upland channel network Moor House. Further research is also needed to monitor changes in the bedrock channel classification over time to establish the key controls that are operating.

7.1 Conclusion

This section summarises the main conclusions from the research. The conclusions are integrated from both results chapters.

- Bedrock channels form 20% of the upper reaches of the Tees catchment. Up to 10% of channels have a bare rock bed with no sedimentation. Classification of the river channel provides a means of determining the importance of bedrock reaches within a catchment by establishing the characteristic properties of bedrock-dominated channel which occurs in the uplands.

- The bedrock classification scheme proposed here allowed the extent and distribution of alluvial sediment to be estimated in both Trout Beck and the Upper Tees channel systems. Although gradual transitions from alluvial to bare rock channels, through a sequence of gradual stages of sedimentation, were recorded (5-4-3-2-1), it was not as common to find a similar gradual transition from bedrock to full alluvial conditions (1-2-3-4-5). Abrupt changes at the end of fully alluvial or bedrock sections could also be found (1-5, 5-1). The Markov chain analysis confirmed these general patterns however the highest transition probability was from class 1 to 2 (62%) occurred for channel classes 4-5 and 2-3 (23 and 67% respectively).

- The classification of the bedrock channel highlighted the local importance of small-scale fluvial landforms and hydraulic conditions on the amount of bed sediment in the river channel.

The study found that sedimentation was more likely to be controlled by the bed conditions (including local gradient) rather than channel boundary conditions and that stream order did not appear to have a major influence on re-sedimentation.

- Re–sedimentation on a reach scale is important and occurs in a variety of different ways. In the study reach both lateral sedimentation and amalgamation of sediment bars, were observed. The lateral sedimentation built slowly from the margins inwards towards the centre of the channel. Sediment bars formed as small nuclei, which gradually grew and joined together. The increase in sedimentation was also accompanied by an increase in clast size within the study reach.

- The rate and spatial pattern of sedimentation is controlled by local hydraulics and the channel discharge regime. Sedimentation appears to be cyclic in nature with large floods depositing significant volumes of sediment which are gradually modified during smaller events. The step-pool sequences within the channel also appear to be important. Due to the increased gradient there is often very little sedimentation in these areas. In the study reach the step-pool sequences within the narrow gorge section have undergone no significant sedimentation through the year. This section is confined by the bedrock gorge sides and also the bedrock bed.

- The results of the tracer study support the view that sediment movement in river channels is episodic. Tracers travelled in small groups, through the channel. The movement through the initial cascade section in the gorge was rapid with only a few tracers deposited in the smaller step-pool sequences (Figure 4.26).

However the majority of the tracers were deposited in a large step-pool at the end of the gorge section (Figure 4.25). This was the main area of sedimentation during the study period.

- Field observations show that bed steps have a significant but highly variable influence on sediment transfer. Field mapping of these steps show that many of the blocks tend to cluster a fixed distance away from the step. It is this distance which is related to block size and also the step height. The step height affects the entrainment and deposition of different block sizes. Block sizes smaller than the step travel further than those larger than the step. The block sizes which are significantly larger than the step (5 cm) also travel further than those a similar height to the step (4 cm), although they are entrained at the same point.

7.2 Limitations

During the study several limitations were noted.

- The bedrock channel classification focused on the main trunk channels, many of the tributaries were not included in the classification. Approximately 40% of the river basin was not surveyed. Therefore the overall percentage of bedrock channels in the study area may be higher because some of the tributaries contain bedrock reaches. Observations suggest this is likely to be a similar proportion or slightly less.

- Recovery rates in the tracers study were generally high, only 16 % of the overall number tracers which were entered into the channel were lost.

Also the lack of large floods due, to dry weather conditions since February meant only two results were recorded for the state logger one of which was unrelated to discharge.

- The frequency of cross sections limited detailed recording of changes in the channel. However fixed point photography and geomorphic mapping provided a valuable supplement to this method.

- Only three bed steps were surveyed, only two of which had blocks of sediment which had been part of the original step. The rock steps surveyed were all extremely different which has provided a set of results which have a considerable variability.

7.3 Extensions of current research.

From the research undertaken it is apparent several key areas require more attention:

1. Classify the tributaries of Trout Beck and the Upper Tees, using the of bedrock classification scheme. This would provide a more comprehensive picture of bedrock channels within this upland catchment.

2. Continue both fixed point photography and geomorphic mapping to monitor the sediment changes within the channel. This will to establish whether the bedrock channel will slowly become fully alluvial over time or whether a further large flood event will wash all of the sediment downstream.

3. Extend the tracer monitoring period to assess whether sediment has moved downstream out of the study reach and see whether the majority of sediment remains in the large pool section. Continue monitoring with the state logger to provide accurate stage information for the transport of different block sizes.

4. A further survey of rock step sedimentation sequences is required. The present study identified a diverse range in the size of rock steps. Further survey of more steps would allow for more accurate determination of the pattern of block movement away from rock steps.

5. Further experimentation in the flume examining rock steps is needed The angle of the bed step in relation to the main flow direction could be varied. In the field rock steps rarely have a front that is orthogonal across the channel. The rock step usually occurs at an angle to the main flow. The influence of this angle on flow and movement of blocks away from the step should be investigated. Further experiments could also be undertaken to provide detailed velocity profiles for different positions of a block away from a bed step.

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