Assessing the importance of river bank erosion for fine sediment delivery to Bassenthwaite Lake

Hopkins, Jonathan

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Jonathan Hopkins

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Durham University, Department of Geography

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DECLARATION

This thesis is the result of my own work and has not been submitted for consideration in any other examination. Material from the work of other authors, which is referred to in the thesis, is acknowledged in the text.

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ABSTRACT

Assessing the importance of river bank erosion for fine sediment delivery to Bassenthwaite Lake

Jonathan Hopkins

Available evidence from lake sediment core records and short-term sediment flux sampling programs has suggested increased fine sediment deposition and suspended sediment transfers to Bassenthwaite Lake, Cumbria, U.K over recent decades. This increase in sedimentation has been associated with a decline in water quality in the lake which is thought to have had serious consequences for the population of the vendace (*Coregonus albula*), which also declined markedly during the 1990s and into the 21st Century. Recent studies of sediment delivery risk in the catchment have suggested that there are potentially large sediment sources in the lowland river network, especially the River Derwent between Derwent Water and Bassenthwaite Lake.

The aim of this research is to describe the characteristics of fluvial suspended sediment transfers to Bassenthwaite Lake through direct monitoring of the River Derwent and Newlands Beck (at the head of Bassenthwaite Lake) in order to assess the potential contribution of river bank erosion on the lowland River Derwent to fine sediment delivery.

Three suspended sediment monitoring stations at Portinscale and Low Stock Bridge on the River Derwent and at Newlands Beck Bridge are used to

assess changes in sediment transport along these important river reaches. The potential contribution of river bank erosion to fluvial sediment delivery was assessed by river bank mapping and surveying of erosion features on the 5.7km reach of the River Derwent between Derwent Water and Bassenthwaite Lake, along with a detailed study of morphological change on three river banks near Low Stock Bridge using a terrestrial laser scanner.

The main findings of this project suggest that the River Derwent dominates suspended sediment transfers to Bassenthwaite Lake. The fine sediment load transported on the Derwent is over five times greater than that of Newlands Beck and the mean suspended sediment concentration on the lower Derwent is 56% higher than that on Newlands Beck. Specific catchment sediment yields for the River Derwent and Newlands Beck, based on effective drainage area, are 50.87 t km^2 a^{-1} and 35.72 t km^2 a^{-1} respectively. A high proportion of all suspended sediment transfers in the lowland Bassenthwaite Lake catchment were observed to occur in high-magnitude, low-frequency flow events, with approximately two-thirds of total suspended sediment transport occurring in just over 10% of the time. There is also direct evidence for increased fine sediment supply on the lowland River Derwent, as an estimated 1,158 t a^{-1} increase in the overall sediment load was observed on the 3.7 km reach of the Derwent between Portinscale and Low Stock Bridge. Hysteresis analysis and analysis of suspended sediment transfers during high flow events on the Derwent support this hypothesis. Overall, 21.1% of all river banks on the River Derwent were

assessed as eroded, with 9.4% of banks undergoing active river bank erosion. Therefore, it is suggested that river bank erosion is a significant fine sediment source in the lowland Bassenthwaite catchment, and that it is responsible for a large proportion of sediment inputs on the lowland River Derwent (c. 18.9%), and ultimately to Bassenthwaite Lake.

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CHAPTER ONE

INTRODUCTION AND PROJECT AIM

Lake sedimentation results from several factors including the physical nature of the catchment upstream of the lake (its geography and geology), human modifications to natural land use patterns, sources of fine sediment and river hydrology, as well as the dynamics of sediment movement in the lake itself (Figure 1.1). At Bassenthwaite Lake, increased fine sediment deposition during the 20th Century to the present day (Section 1.4) is thought to be the result of increases in suspended sediment transfers from the catchment upstream of the lake.

The decline in water quality at Bassenthwaite Lake has led to significant ecological problems, including the dramatic decline in population of a rare species of freshwater fish, the vendace (*Coregonus albula*) (Table 1.2). It is hypothesised that much of the deterioration in water quality is a result of increased fine sediment delivery. However, there are significant uncertainties as to the nature of suspended sediment transfers in the lowland Bassenthwaite Lake catchment, in particular overall sediment loads, the relative importance of the River Derwent and Newlands subcatchments, and the spatial distribution of fine sediment sources in the catchment. Additionally, recent studies of sediment supply risks in the catchment have suggested that the increasing suspended sediment input to Bassenthwaite Lake may be caused by greater sediment fluxes from the lowland catchments, and that sediment delivery risks in these areas are high (Orr et al. 2004).

The aim of this research project is to describe the characteristics of fluvial suspended sediment transfers to Bassenthwaite Lake through direct monitoring of the River Derwent and Newlands Beck (at the head of Bassenthwaite Lake) in order to assess the potential contribution of river bank erosion on the lowland River Derwent to fine sediment delivery.

This chapter describes Bassenthwaite Lake and its catchment (Sections 1.1, 1.2) and the present ecological problems in the lake (Section 1.3) that are thought to result from a decline in water quality, partly as a result of increased sediment deposition (Section 1.4) as well as increased nutrient contents of the lake (Section 1.5). The main research questions are outlined at the end of the chapter (Section 1.6).

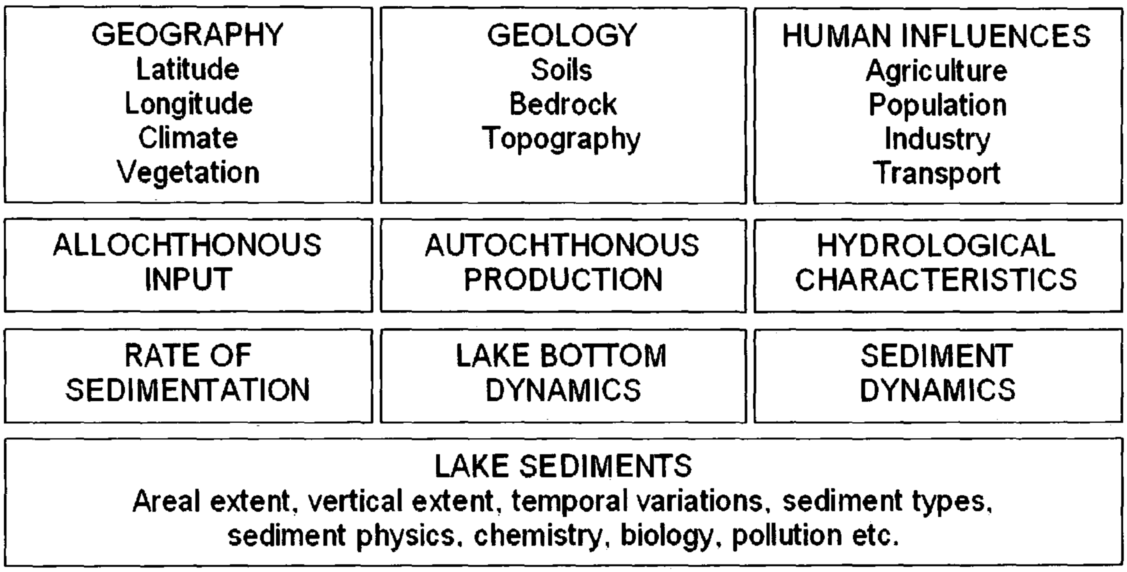

Figure 1.1: Factors which influence the nature of lake sediments and sedimentation. Adapted from Håkanson and Jansson (2002).

1.1 Lake and catchment characteristics

Bassenthwaite Lake (Figure 1.2) is located in the Lake District, Cumbria, and is the most northerly of its major lakes, situated c. 5km to the north-west of the town of Keswick. The lake's importance as an ecological habitat, especially to the rare vendace *(Coregonus albula)*, is discussed below, and provides the main justification for this project.

Figure 1.2: Aerial photograph of Bassenthwaite Lake, looking north-west along the lake from above Portinscale. The A66 road is visible on the west (left) side of the lake. The two main watercourses flowing into the lake are visible flowing across the wide floodplain. The River Derwent is visible on the far right of the photograph, flowing into the lake to the east of its former delta. Newlands Beck is visible flowing in an enclosed channel through the large area of marshes in the centre of the floodplain.

Bassenthwaite Lake is notable for having the largest catchment area of any of the Lake District's lakes (347 km^2). It has two main tributaries, the River Derwent and Newlands Beck which flow into the south end of the lake, as well as minor tributaries including Chapel Beck and Dash Beck which flow into the north-east sector of the lake. The River Derwent has a much larger total catchment area (235 km^2 upstream of Portinscale) than Newlands Beck (33.9 km^2 upstream of Newlands Bridge) (source: National River Flow Archive), and comprises the dominant hydraulic input to Bassenthwaite Lake, accounting for c. 80% of the total water input (Hall et al. 2001). The Derwent has an estimated daily hydraulic load of 1,097 million litres, compared with loads of 136.9 million litres from Newlands Beck and 49.2 million litres from Chapel Beck (Beattie et al. 1996). The River Derwent flows from Borrowdale, collecting water from a large area of the Lake District's central fells (Figure 1.3). The river flows into Derwent Water, and at Portinscale the Derwent has a confluence with its major tributary, the River Greta at NY 256 236, before meandering across a wide floodplain and flowing into Bassenthwaite Lake. Between the two lakes, the Derwent is 5.7 km long (Figure 1.3). The Greta is a large river in its own right, which drains the western and northern slopes of the Helvellyn range, Thirlmere reservoir and a large area of the northern fells around Blencathra. Newlands Beck carries the drainage of the Newlands Valley, Coledale and several subsidiary valleys of the Crag Hill and Dale Head ranges. Chapel Beck drains an area of the fells to the north of the Skiddaw massif.

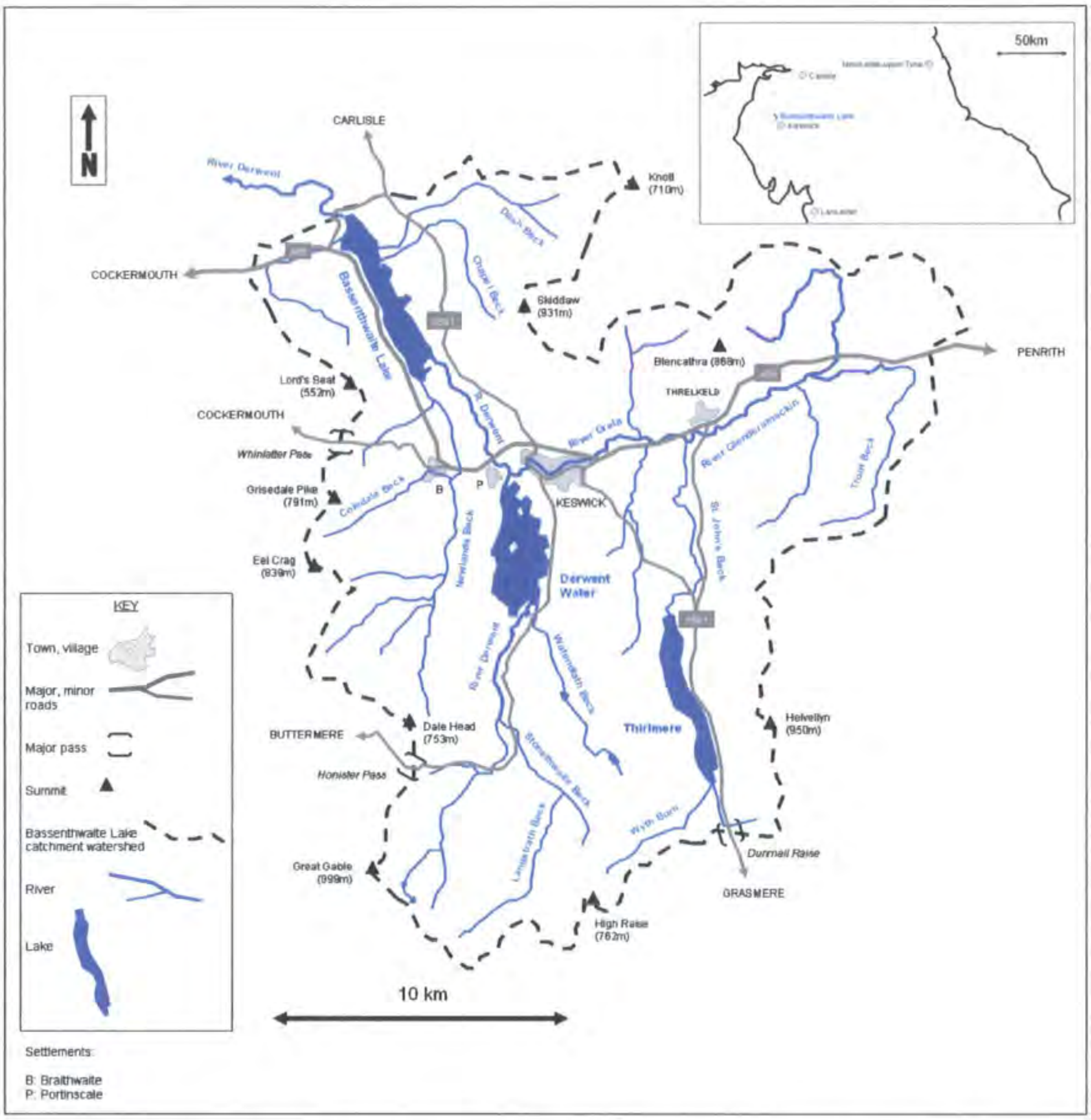

Figure 1.3: Map of the Bassenthwaite Lake catchment showing principal settlements, lakes, rivers and mountains, with its position in Northern England indicated (top right).

The main features of Bassenthwaite Lake are summarised in Table 1.1. The lake's most notable characteristic is its shallowness, having the smallest maximum depth of the major lakes in the region (20 m). The majority of the lake basin (66%) is below 5 m in depth (Reynolds 1999), with the northern and southern reaches being especially shallow (Ramsbottom 1976). Combined with the high volume of water entering the lake, this leads to a regular replacement of lake waters, with an average residence time of only 19 days (Reynolds 1999, Maberly and Elliot 2002). The shallowness of the lake means that its water level has recorded rises of up to 1 m during floods (Stokoe 1983), and renders the lake more vulnerable to sedimentation than deeper, higher volume water bodies.

Bassenthwaite Lake	
Altitude	69 m
Area	5.28 km^2
Depth	maximum 20 m, mean 5.3 m
Catchment area	347 km^2
Mean annual hydraulic discharge	544,000,000 m^3 a^{-1}
Mean hydraulic residence time	19 days

Table 1.1: Hydrometrical and limnological characteristics of Bassenthwaite Lake. Adapted from Reynolds (1999).

The catchment of Bassenthwaite Lake is dominated by high mountains and upland moors. Large areas of the catchment watershed are in excess of 800 m in height; including Helvellyn (950 m), Skiddaw (931 m) and Blencathra (868 m), as well as the mountains at the head of Borrowdale and the large area of fells to the west of Derwent Water. There are extensive areas of peat moorland in the catchment, including the broad ridge between Derwent Water and Thirlmere and the moors to the north of Skiddaw. The catchment is dominated by upland areas, as open (non-enclosed) fellside covers some 54% of the total catchment area (Orr et al. 2004).

1.2 Geology and glaciation

Geologically, Bassenthwaite Lake is underlain by Skiddaw slates. These are the oldest exposed rocks in the region (Moseley 1978), and were formed c. 500 million years ago. Such rocks are easily eroded, and this characteristic has led to the fells in the Skiddaw slate ranges having characteristically smooth slopes, with extensive talus and scree deposits. This is especially notable on Skiddaw itself and the Grisedale Pike and Eel Crag ranges (Figure 1.3). The landscape in the northern part of the catchment is in great contrast to the uplands in the region of Borrowdale and the central Lake District fells. This area is characterised by a spectacular landscape of high relief, with steep slopes and exposed rocks. This is as a result of the more erosion-resistant Borrowdale Volcanic rocks composed of andesitic lavas, fine-grained tuffs and pyroclastic deposits that are the remnants of a volcanic dome which formed c. 50 million years ago (Moseley 1978, Smith 1992). The steep slopes are associated with poor soils, slope instabilities and extensive areas of bare ground, which leads to a high potential for sediment delivery from these areas (Orr et al. 2004).

The upland areas of the catchment comprise an excellent example of a formerly glaciated landscape. There is some debate about the maximum depth of ice over the Lake District, but a mapping of weathering limits in the central fells suggested a maximum ice depth of c. 870 m during the Last Glacial Maximum (c. 21 ka BP) (Lamb and Ballantyne 1998). Although the ice was of significant depth, and confluent with Scottish ice sources, the Lake District maintained a topographic control over ice flow directions, leading to a radial ice discharge pattern and several U-shaped valleys descending from what is today the central Scafell massif. Glacial scouring led to the production of overdeepenings, which are today occupied by lakes. Furthermore, classic glacial features including corries are in evidence on the high fells, largely formed during the shorter cold period of the Younger Dryas/Loch Lomond Stadial (12.9-11.5 ka BP) (Sissons 1980, McDougall 2001). Also, large volumes of alluvium and debris were deposited across the lowlands, creating expanses of low relief that formed the basis of floodplain development. Paraglacial slope processes (Ballantyne 2002) and fluvial erosion have been important agents of morphological change in the region since deglaciation (Boardman 1992, Wilson 2005), notably the formation of floodplains by overbank flooding that continues to the present day. Therefore, an ongoing transfer of sediment from the catchment uplands to lowland areas is occurring, largely through fluvial transport.

1.3 Lake ecology and vendace decline

Bassenthwaite Lake is a National Nature Reserve and a Grade 1 Site of Scientific Interest. Extensive ecological monitoring of the lake has taken place over the last 50 years, and particularly since the 1990s to present, due to growing concerns for the population of the freshwater vendace (Table 1.2 below). In addition to the vendace, 10 species of fish have been recorded in recent surveys of the lake (Thackeray et al. 2006) although the lake is home to few 'native' British fish (Winfield and Durie 2004).

The vendace (*Coregonus albula*) is a medium-sized coregonid fish which is found across Northern European regions, especially Scandinavia, although it is very rare in the United Kingdom. Up until the mid-20th Century the fish was found in four lakes in the UK, with well-documented populations in south-west Scotland at Castle Loch and Mill Loch (Maitland 1966) in addition to the populations in Bassenthwaite Lake and Derwent Water. However, the two Scottish populations are now thought to be extinct (Winfield et al. 1998) meaning that the two Lake District lakes now comprise the only habitat for vendace in the country. The fish have a narrow habitat preference, which includes the need for low water temperatures (Hamrin 1986), high concentrations of dissolved oxygen (Dembinski 1971) and a clean substrate in spawning areas (Wilkonska and Zuromska 1992). Threats to the species include its predation by larger species, including the roach (Auvinen 1988, Winfield and Durie 2004). However the dominant threat to the fishes survival in Bassenthwaite Lake is declining water quality, especially increased inorganic fine sediment delivery (Section 1.4), as well as increases in nutrients and phosphorus concentrations (Section 1.5). Sedimentation in vendace spawning gravels is critical to controlling the vendace population, as sediment deposition in such areas prevents the passage of oxygenated water to incubating fish eggs, preventing spawning (Greig et al. 2005). Additions of nutrients to the lake (especially phosphorus) can lead to the excessive growth of algae and lake plants, causing eutrophication, which greatly reduces the dissolved oxygen content of the water, which constitutes an essential requirement for vendace spawning and survival (Dembinski 1971, Winfield et al. 2004).

Study	Population details
Regan 1908	First record of species' presence in Bassenthwaite Lake.
Maitland 1966	Thriving population.
Broughton 1972	Good population, though limited data.
Mubamba 1989	Good population although decline in numbers of juveniles and young fish – possible link with increased sedimentation from the building of the A66 Keswick bypass in the 1980s.
Atkinson et al. 1989	Large population, "several tens of thousands of fish", but notes vulnerability to eutrophication and siltation. "All the evidence suggests that continued increases in nutrient loading... will lead inexorably to the *extinction* of this population (of vendace)"
Winfield et al. 1994	Population status unclear (initial study in June 1992 suggested dominant age group = 4-5 years old, November 1992 study suggested dominant class = 2 years old), but large amounts of organic material, siltation of gravel beds and absence of macrophytes renders vast majority of lake poorly suited to vendace spawning.
Winfield et al. 1996	Poor population status. Notably aging population (poor recruitment to post-juvenile population, 60% of all fish age 4 years). Low density of post-juvenile vendace when compared with sites in Scandinavia.
Winfield et al. 1998	Study of spawning grounds suggested poor conditions and widespread siltation, reliance upon limited growth of macrophytes to provide conditions for spawning rather than suitable sediments, need for "direct intervention" to arrest population decline.
Winfield et al. 2002	Continuing aging of population (all but one of vendace sampled 6 years or older), decline of numbers resulting from siltation of spawning beds and predation (roach).
Winfield et al. 2004	High inter-annual variability in numbers but marked decline in population of post-juvenile vendace from in excess of 250,000 (2000-2001) to less than 100,000 (2002) and less than 50,000 (2003).
Lyle et al. 2005	Concern for future of vendace in the catchment, attempts to translocate population to Bowscale Tarn and other sites.
George et al. 2006	Habitat for vendace in Bassenthwaite Lake is now extremely limited.

Table 1.2: A summary of the literature on vendace populations in Bassenthwaite Lake and the condition of vendace spawning beds.

The studies and surveys summarised above (Table 1.2) indicate a dramatic population decline and a markedly deteriorating habitat in Bassenthwaite Lake. The population appears to have been healthy until around 1990, and the studies by Mubamba and Atkinson et al. in 1989 were the first to indicate an aging population structure and the increased vulnerability of the species to habitat changes, despite the continuing strong population numbers. From 1990, regular research was carried out by Winfield and others at the Institute of Freshwater Ecology, and throughout the 1990s the population was seen to decline with continued aging and low recruitment of young vendace, as a result of the extensive sedimentation of spawning beds, leading to an over-reliance on macrophytes as spawning areas as a result of the lack of suitable gravels (Winfield et al. 1998). Over the current decade, the deterioration in the vendace populations has continued, with recent studies raising severe concerns for the continued survival of the species in Bassenthwaite Lake. This has led to an interest in monitoring sedimentation in the lake and sediment delivery from the lowland catchment (Section 1.4).

1.4 Sedimentation rates in Bassenthwaite Lake

Despite concerns over sedimentation in the catchment, there have been relatively few surveys of historical sedimentation rates. Sediment cores have been extracted from the lake, providing longer-term records of the past few hundred years (e.g. Cranwell et al. 1995, Bennion et al. 2000). Such records have provided the most useful information of historical sedimentation rates. The former study used a range of 1 m cores in the deepest part of the lake, and carried out diatom analysis as well as isotopic dating. It suggested an increase in sedimentation rates from 0.05 g cm a^{-1} in the late 19th Century to 0.11 g cm a^{-1} at the present day, along with a decline in water quality. There were correlations between periods of railway construction and mining activity with peaks in the sediment accumulation rate. Similar overall sedimentation rates were discovered by Bennion et al. (2000) who used radiometric dating to analyse changes in sedimentation rates, and observed a large increase in accumulation over the first 40 years of the 20th Century (from 0.05 g cm a^{-1} to 0.14 g cm a^{-1}), with the increased rate sustained to around the present day (mean rate c. 0.1 g cm a^{-1}). Diatom analysis of this core suggests a reduction in the lake's oxygen levels during the same period, supporting the increased sedimentation and also possible eutrophication. These longer term studies are by far the most useful records of sedimentation rates in Bassenthwaite; shorter-term studies (e.g. Parker et al. 1999, Hall et al. 2001) are inconclusive and show large variations in sediment accumulation over a relatively short period of time.

There is some uncertainty as to the overall suspended sediment load being carried to the lake by rivers. This is largely due to the short-term nature of most river sampling, and the use of inadequate sampling methods that do not account for the large volumes of suspended sediment transferred during high flow events. However, turbidity monitoring carried out during 2006 for this project suggests that the River Derwent dominates the suspended sediment input to the lake (Chapter 4). The use of automatic river water samplers and continuous turbidity monitoring has led to an arguably more reliable record than that of Parker et al. (1999) whose load calculations were based upon fortnightly samples only. Controversially, Hatfield and Maher (2006) have used magnetic fingerprinting to argue that Newlands Beck is the main source of sediment delivery to Bassenthwaite Lake, arguing that the tributary is transport-dominated in comparison with the River Derwent, whose channel and floodplain are storage areas for large quantities of sediment. A further hypothesis has suggested that sedimentation in the lake basin is a result of fine sediment mobilisation from the lake itself, as a result of gale-force winds (Parker et al. 1999). However, the majority of the studies described in this section argue that sources of fine sediment in the catchment upstream of the lake are most important to the increased sedimentation rate, and these sources comprise the focus of this project.

1.5 Nutrients in Bassenthwaite Lake

Studies of the nutrient status of the water have also been undertaken as the removal of dissolved oxygen from the lake by eutrophication (as a result of nutrient addition and excessive algal/plant growth) significantly affects the vendace population (Dembinksi 1971, Winfield et al. 2004). Atkinson et al. (1989) compiled a record of lake surveys between 1920 and 1988 which showed increasing concentrations of nitrate-nitrogen and phosphorus in the lake (Table 1.3), suggesting worsening eutrophication. This corresponds well with longer-term sediment records of the lake, whose diatom records suggest a change from mesotrophic to eutrophic conditions since 1900 (Cranwell et al. 1995). The overwhelming source of phosphorus to the lake in recent years has been Keswick Waste Water Treatment Works, which provided nearly 78% of total phosphorus load to Bassenthwaite Lake in 1993 (Thackeray et al. 2006). In 1995 a treatment scheme was implemented at the works, and there is evidence of a slight improvement in water quality, suggested by increased Secchi disk depths and a reduction in annual phosphorus maxima (Reynolds et al. 2002, Thackeray et al. 2004, Maberly et al. 2004, 2006). Now, around 50% of total phosphorus input to Bassenthwaite comes from catchment sources (Orr et al. 2004), potentially through the erosion of field drains and livestock poaching (Dils and Heathwaite 2000). An advantage of the shallow Bassenthwaite Lake is the regular turnover and replacement of lake waters (Table 1.1) although this has not prevented the phosphorus concentration increase. The impact of such nutrient loading has been an increase in populations of phytoplankton, diatoms and algae (e.g. Reynolds et al. 1998, 2000), a phenomenon also noted in Derwentwater with phytoplankton increases (Maberly et al. 2006). There is little evidence however that oxygen concentrations are declining in Bassenthwaite, although Thackeray et al. (2004) did note that oxygen concentrations at depth remained low in 2004 (<1 mg l^{-1}) for longer than recorded previously.

Survey year	Total NO_3-N (µg l^{-1})	Total P (µg l^{-1})
1928	91.9	2.1
1946		
1949	151	1
1955-1956	252	
1971		0.85
1974-1976	224	
1984	390	1
1987-1988	370	5

Table 1.3: Generally increasing nitrate-nitrogen and phosphorus concentrations in Bassenthwaite Lake as shown by surveys through the 20th Century. Adapted from Atkinson et al. (1989).

1.6 Project aim and research questions

The overall aim of this research is to describe the characteristics of fluvial suspended sediment transfers to Bassenthwaite Lake through direct monitoring of the River Derwent and Newlands Beck (at the head of Bassenthwaite Lake), and to assess the potential contribution of river bank erosion on the lowland River Derwent to fine sediment delivery. Therefore, the two key research questions are:

1. What are the characteristics of suspended sediment transfers to Bassenthwaite Lake?
2. To what extent does river bank erosion constitute an important fine sediment source on the lowland River Derwent?

To answer the first research question, the nature of suspended sediment transfers on the River Derwent and Newlands Beck had to be assessed, with reference to the overall characteristics and spatial variations in suspended sediment transport as well as the calculation of overall sediment loads. The second question required an analysis of the overall extent and characteristics of river bank erosion on the River Derwent. The following literature review (Chapter 2) considers the potential suspended sediment sources within the Bassenthwaite catchment, including an analysis of the evidence for river bank erosion in the lowland catchment and an overview of river bank erosion processes in temperate catchments, which was used to plan an appropriate methodology and set of field techniques (Chapter 3) to collect data and address the research questions above. Results and analysis are reported in Chapter 4. The thesis concludes with Chapter 5 and includes recommendations for further research.

CHAPTER TWO

LITERATURE REVIEW

As the aims of this project are to assess suspended sediment transfers to Bassenthwaite Lake and the importance of river bank erosion as a source of fine sediment (Section 1.6), this literature review aims to review the current state of knowledge in these areas. Section 2.1 outlines the importance of fine sediment sources within the Bassenthwaite Lake catchment to suspended sediment transfers to the lake itself, and describes the importance of processes of fell erosion (Section 2.1.1) and sediment delivery from different land uses (Section 2.1.2). Section 2.2 describes the evidence for widespread, active river bank erosion on the River Derwent. Section 2.3 describes the precipitation input to the catchment. Section 2.4 comprises a detailed discussion of the processes and mechanisms of river bank erosion, factors influencing river bank stability, temporal and spatial trends in bank erosion rates and an analysis of the potential contribution of river bank erosion to sediment budgets.

2.1 Assessment of fine sediment sources within the Bassenthwaite Lake catchment

As a result of the increased sedimentation rate in Bassenthwaite Lake observed during the 20th Century (Section 1.4) and the resulting decline in water quality and decrease in vendace population (Section 1.3), there has been an increase in interest in potential sources of fine sediment in the Bassenthwaite

Lake catchment. Figure 2.1 shows that sediment sources within the catchment are created through the interaction of climate (in particular precipitation inputs), the physical characteristics of the catchment, and land use changes. These sediment sources become suspended sediment inputs where they interact with the fluvial system and are able to be transported by the stream and river network. River bank erosion, along with channel erosion, comprises a further suspended sediment input. The ecological problems within Bassenthwaite Lake and the decline in the vendace population (Section 1.3) result from the deposition and storage of this fine sediment in the lake. Lake erosion, and resuspension of fine sediment from the lake bed, also produce fine sediment which may be stored or transported out of Bassenthwaite Lake (Figure 2.1). Therefore, the interactions between fine sediment sources and the fluvial system are very important to the ecology of Bassenthwaite Lake, but are presently poorly understood, in particular the relative importance of individual sediment sources and the contribution of suspended sediment from individual sub-catchments, which has been identified as a research need (Orr et al. 2004). Previous studies have identified sediment losses from source areas but have been unable to determine how much reaches Bassenthwaite Lake, and over what time duration. The bank erosion on the lower River Derwent was thought to be a potentially significant direct source of fine sediment to lake shore gravels and vendace spawning sites. The results from newly established suspended sediment monitoring sites and some novel approaches to surveying bank erosion are used in this study in an attempt to quantify the contribution to overall sediment delivery along the reach of the

Derwent immediately upstream of Bassenthwaite Lake. By quantifying suspended sediment transfers to Bassenthwaite Lake from the River Derwent and Newlands Beck sub-catchments, and further analysing the specific contribution of river bank erosion to the sediment budget, it is hoped that this project will lead to a greater understanding of fine sediment transfers in the Bassenthwaite Lake catchment and therefore inform mitigation measures which could be used to reduce fine sediment delivery to the lake.

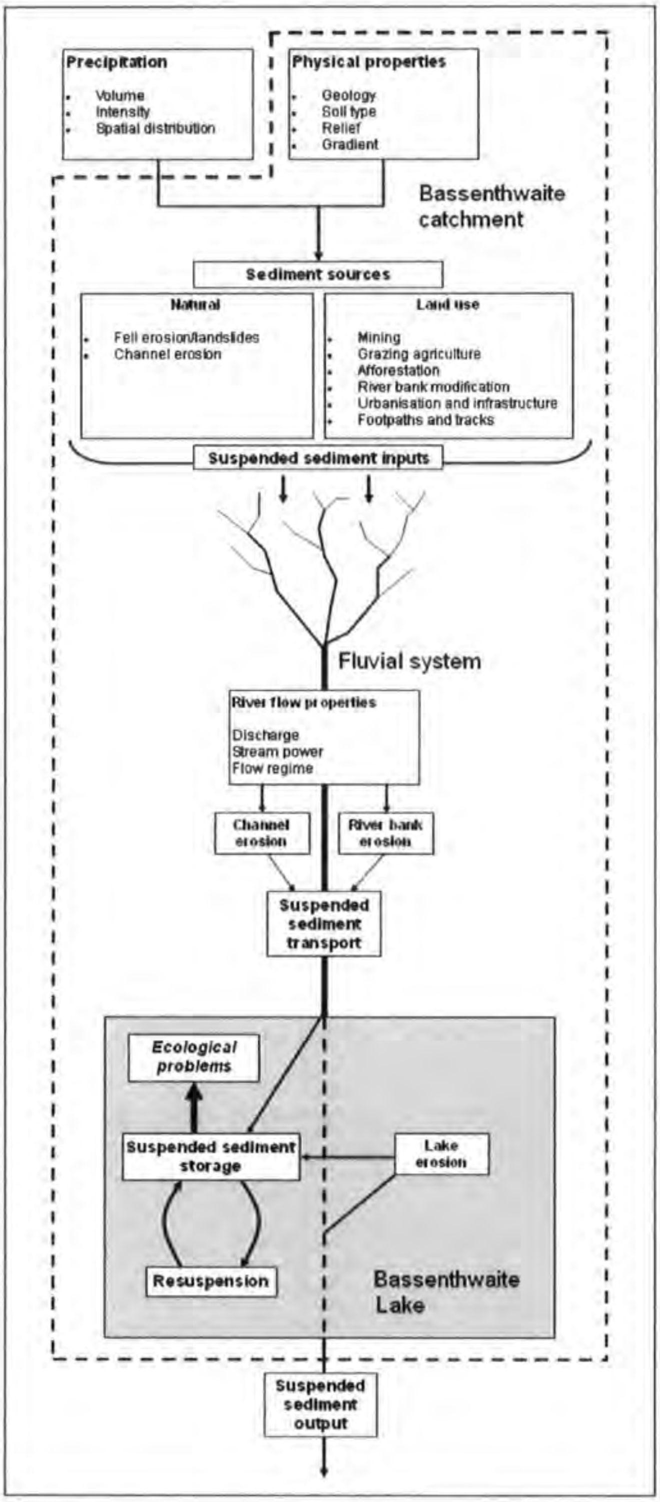

Figure 2.1: The relationships between fine sediment sources, suspended sediment inputs and transfers, the fluvial system and the ecological problems in Bassenthwaite Lake.

The geomorphological assessment of the Bassenthwaite Lake catchment by Orr et al. (2004) suggested that both natural sediment sources and land use changes have the potential to provide fine sediment to Bassenthwaite Lake (Table 2.1). River bank erosion was assessed to be a particularly significant source of sediment to the lake, due to the large volume of erosion described as taking place and the direct connection to the channel network; although a much larger amount of erosion was taking place on the fells, the remoteness of much of this erosion from the fluvial system meant that fell erosion was only likely to be a significant sediment source to the lowland catchment over longer timescales (Table 2.1).

Sediment source	**Quantity (m^3) (2004 study)**	**Direct connection to channel network?**	**Impact on sedimentation of the lake**
Fell erosion	4,000,000	No	Significant*
Bank erosion	**15,000**	**Yes**	**Significant**
Field drainage	Unknown	Yes	Significant
Mine waste	10,000	Yes	Less significant

*Table 2.1: A summary of some fine sediment sources and their potential impact on the sedimentation of Bassenthwaite Lake, with river bank erosion highlighed. * - over longer timescales. Adapted from Orr et al. (2004).*

While catchment fine sediment sources (located upstream of Bassenthwaite Lake) are now known to be highly significant to sedimentation rate increases, the effects of lake bed erosion have also been thought to be significant in fine sediment mobilisation (e.g. Parker et al. 1999). Wave erosion of the lake floor is thought to be facilitated by the long fetch of northerly winds, and encouraged by the shallowness of large areas of the lake. Additionally, gale-force southerly winds with speeds in excess of 20 m s^{-1} could affect the bed of the shallow southern parts of the lake (Parker et al. 1999). Such mechanisms and processes are thought to operate in other shallow lakes (Hilton 1985, Bloesch 1995). The lake's susceptibility to this form of erosion makes it a potentially important fine sediment source, however the analysis of catchment suspended sediment sources, in particular river bank erosion, are the focus of this project.

2.1.1 Fell erosion

Naturally-occurring processes of erosion that may constitute fine sediment inputs to the Bassenthwaite Lake catchment include fell erosion and river bank erosion. The erosion of sediment from the fells includes landslide and mass movement processes and the erosion of mountain torrents and other low order streams in the catchment, with the potential for the delivery of large volumes of sediment following storms and heavy rain (e.g. Kelsey 1980, Wells and Harvey 1987). Unstable areas of scree and bare ground can also comprise important sources of fine sediment if they are in close proximity to areas of overland flow generation and stream networks. Orr et al. (2004) estimated that 20-25% of the Bassenthwaite catchment featured soils with a high risk of erosion (Figure 2.2), based upon an analysis of areas of bare ground and an assessed high risk of poaching, general erosion, water logging and surface run-off. The areas with the greatest erosion risk appear to coincide with areas of high relief and altitude, with particularly high risks near the mountains of Great Gable, Dale Head, Skiddaw, Blencathra and Helvellyn (Figure 1.3, Figure 2.2). However, there are poor linkages between areas of erosion in the catchment uplands and the fluvial system, meaning that fell erosion is thought to be only significant as a sediment source over long timescales (Orr et al. 2004, Table 2.1).

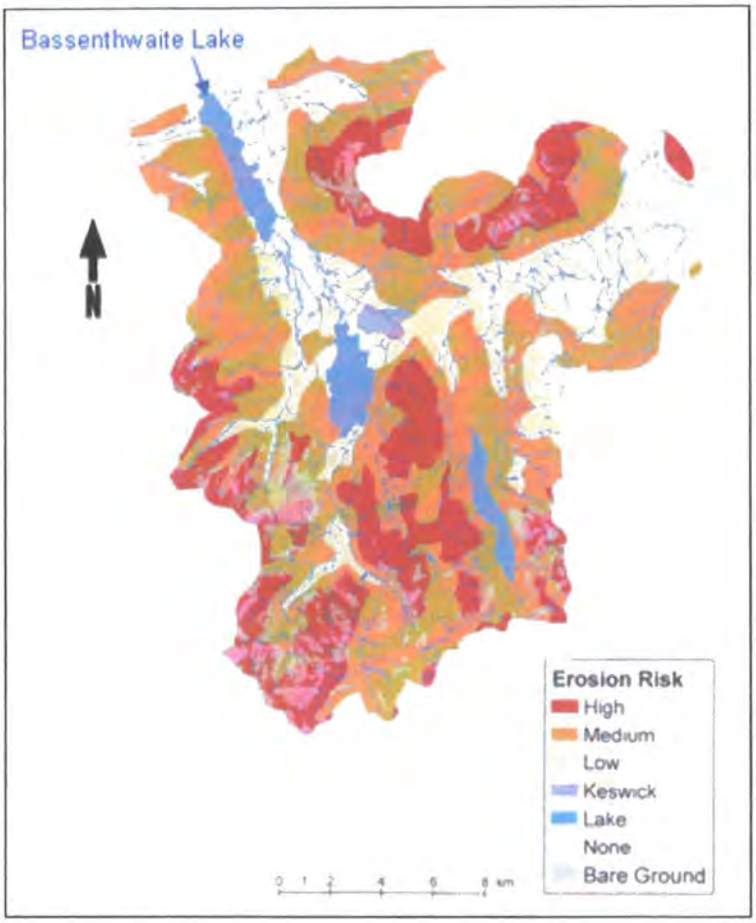

Figure 2.2: Soil erosion risks in the Bassenthwaite catchment, showing high erosion risks in many of the upland areas in the southern catchment. Adapted from Orr et al. (2004).

2.1.2 Land use

The current pattern of land use in the Bassenthwaite Lake catchment reflects centuries of its modification by humans. However, the increased sedimentation rate in the lake observed in core sediments (Cranwell et al. 1995, Bennion et al. 2000, Section 1.4) occurred largely during the first half of the 20th Century. This corresponds in particular to a rise in sheep numbers and the density of agricultural grazing, the mechanisation of mining in the catchment, increased afforestation and a period of population growth and infrastructure expansion over the latter part of the 19th Century and early 20th Century. Such patterns have been recognised as key factors in determining overall sediment delivery in the catchment (Orr et al. 2004).

The Bassenthwaite Lake catchment is dominated by agriculture, as the upland fells (54% of catchment area) are used for extensive, rough grazing and an additional 30% of the catchment is comprised of enclosed grazing land (Orr et al. 2004). Increasing areas of improved pasture and increased stocking densities is frequently associated with greater sediment delivery from these areas, as observed by van der Post et al. (1997) at Blelham Tarn in the southern Lake District, and in wider catchment studies in the UK (e.g. Francis and Taylor 1989, Owens et al. 1999, Sullivan et al. 2004). Grazing, particularly in lowland areas, leads to soil compaction, a reduced infiltration capacity and therefore higher volumes of potentially erosive surface run-off following rainfall (Heathwaite et al. 1990). A key impact of grazing in riparian areas is the formation of distinctive areas of bare ground and loosened surface material, known as poaching scars (Evans 1997, Figure 2.3), which are often found at sheltered river banks and are rarely revegetated due to continued grazing (Tallis and Yalden 1983, Anderson and Radford 1994). Such scars frequently form on river banks where agricultural land borders the channel (Figure 2.3), and loosened material can be easily entrained by high flows. In some upland grazing areas, including the northern slopes of Skiddaw (Figure 1.3), the installation of networks of drainage channels known as grips has taken place (Figure 2.4) in order to increase the area of grazing land. The erosion of such grips has the potential to contribute fine sediment to the lowland catchment, with additional increases in peak flows following the installation of upland drainage networks (e.g. Conway and Millar 1960, Knighton 1973).

Figure 2.3: Poaching scars at Portinscale (left) and Low Stock Bridge on the River Derwent, Cumbria (right) showing trampled, disturbed fine sediment in areas of grazing.

Figure 2.4: Grips at Candleseaves Bog (NY 277 304) near Skiddaw House, showing parts of the network of narrow and deep (maximum depth c. 1m) drainage channels cut into the peat bogs on heather moorland close to the Derwent/Eden watershed.

Aside from grazing, other major land uses in the catchment include woodland (11% of the catchment area, including 7% of conifer plantations) and urban areas (1.5% of catchment area), as well as more localised sources of fine sediment including former mining areas and eroded footpaths. The soil disturbance associated with processes of afforestation and deforestation have been known to increase sediment delivery from these areas (e.g. Anderson 1954, Megahan 1972, Robinson and Blyth 1982, Battarbee et al. 1985). However, mature forest cover is generally thought to reduce sediment erosion risks, and the plantation of woodland in 'buffer zones' alongside river channels and near areas with high erosion risk has been proposed as a means of reducing fine sediment transfers in the Bassenthwaite Lake catchment (Nisbet et al. 2004, AXIS Consultancy 2007). Although only a small area of the catchment is urbanised (the largest settlements being Keswick, Portinscale and Braithwaite (Figure 1.3)), a major expansion of the road infrastructure in the area occurred during the 1970s when the A66 was extended past Keswick and Bassenthwaite Lake. Fine sediment release from this road building has been proposed as contributing to an increased sedimentation rate in Bassenthwaite Lake (Mubamba 1989, Orr et al. 2004). Furthermore, river bank modifications have been made at Keswick and Portinscale in the form of stone revetments as a means of erosion protection and flood defence, and similarly much of Newlands Beck has been straightened and had its banks reinforced and raised (Figure 2.5). These modifications can lead to increases in river flow velocity, and therefore a greater potential for downstream channel erosion. Importantly, increases in river bank height reduce the frequency of overbank flooding, disconnecting the river channel from its floodplain and increasing the proportion of suspended sediment transported downstream. Finally, wooden revetments were installed on several parts of the River Derwent during World War II. However, many of these revetments have since fallen into disrepair, which means that the river channel is able to adjust its course, contributing to river bank erosion (Orr et al. 2004, Figure 2.6). Overall, in addition to natural sediment sources, land use changes in the Bassenthwaite Lake catchment have caused additional sediment inputs and probable increases in fine sediment transfers to Bassenthwaite Lake.

Figure 2.5: Channel regulation on Newlands Beck, showing channel straightening and bank heightening and reinforcement using (left) boulder revetments (NY 238 221) and (right) wooden revetments at Newlands Bridge (NY 240 263).

Figure 2.6: A line of ruinous wooden revetments in the River Derwent's channel at erosion study bank 2 near Low Stock Bridge (NY 237 266), showing obvious retreat and erosion of the bank back from the revetments.

2.2 River bank erosion

A survey of the location and extent of bank erosion in the Bassenthwaite Lake catchment was undertaken by Orr et al. (2004), however no calculations have been made to estimate erosion rates, eroded volumes or the susceptibility of river banks to further erosion. However, the close proximity of the extensive eroded river banks on the River Derwent to the fluvial system and Bassenthwaite Lake means that it has been assessed as a potentially significant source of fine sediment (Orr et al. 2004, Table 2.1). There are three sources of information available which suggest that river bank erosion is both extensive and active on the Derwent floodplain:

- Field observations of eroded river banks
- A high assessed risk of sediment delivery, indicated by studies of sediment sources and channel typologies
- Changes to the River Derwent's course, indicated by comparisons of modern and historical maps.

River bank erosion is accentuated on the River Derwent's floodplain due to two general factors. Firstly, the composition of the River Derwent's banks, which are primarily made up of fine alluvial material and overbank floodplain deposits, as well as gravel layers. The properties of these materials render them vulnerable to mass failures, in particular by cantilever and rotational mechanisms, depending upon variations in local bank structure (Section 2.4.2). Secondly, many of the river banks are high and steep, and therefore particularly vulnerable to failures by undercutting and slumping (Section 3.1). A detailed description of processes and mechanisms of river bank erosion is contained in Section 2.4.

2.2.1 Field observations of river bank erosion

Observations of the river banks on the River Derwent suggest that they are in the process of active erosion (Figure 2.7). Several of the river banks show evidence of:

- exposed material
- undercutting and overhang development
- slumped material
- failed block accumulation at the bank foot
- turf slippage at bank top and tension cracks
- talus slope accumulation

Additionally, anecdotal evidence suggests the presence of active bank erosion episodes, especially during flood events. A local farmer suggested that a river bank near High Stock Bridge had retreated by c. 2-3 m during the flood event of December 2006 (Harley 2007, personal communication). Although such estimates are difficult to quantify, they are an important source of information as they support the field observations listed above.

Figure 2.7: Examples of eroded banks on the River Derwent. Top row: at Portinscale (left), upstream of Low Stock Bridge (right). Bottom row: eroded river banks downstream of Low Stock Bridge.

2.2.2 Studies of channel typologies and sediment delivery risks

Estimates of the significance of bank erosion as a sediment source in the Bassenthwaite Lake catchment have been made by Orr et al. (2004) (Table 2.1), which suggests that river bank erosion has a potentially important impact upon lake sedimentation. The survey produced a figure of overall sediment volume added to the catchment's sediment budget by bank erosion (15,000 m^3), which was a potentially significant sediment source due to the direct input to the river channel.

The research of Orr et al. (2004) also used a classification of bank and channel characteristics in order to assess sediment erosion risks from riparian areas, suggesting a high risk of sediment erosion on the River Derwent between Derwent Water and Bassenthwaite Lake (Figure 2.8). The close proximity of this river reach to Bassenthwaite Lake means that it may be an important source of sediment to the Lake. Other areas of high erosion risks near Bassenthwaite Lake include some parts of Newlands Beck and some upland streams to the north and west of Skiddaw (Figure 2.8).

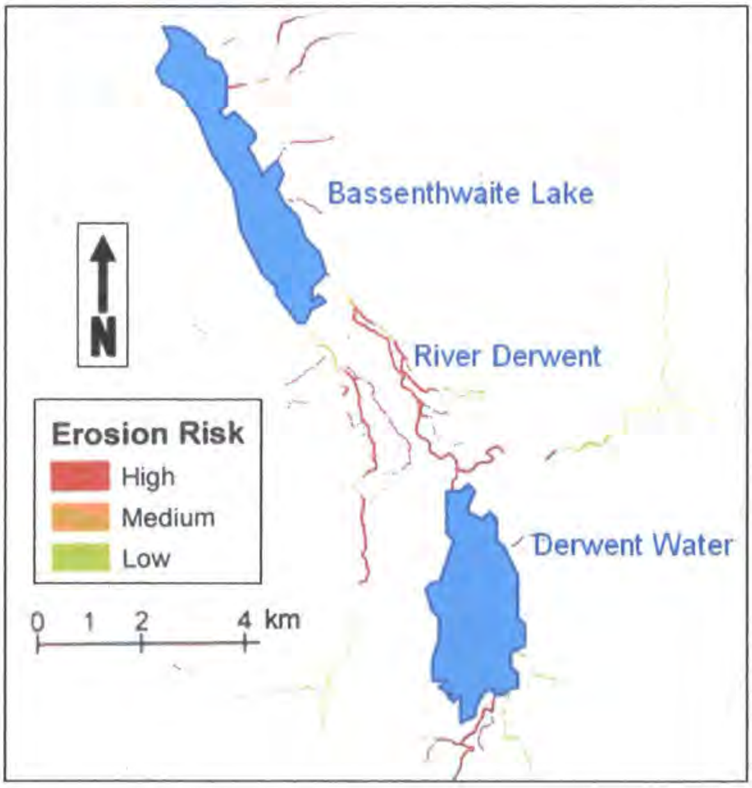

Figure 2.8: Soil erosion risks in riparian areas of the lowland Bassenthwaite Lake catchment, showing a high erosion risk on the River Derwent between Derwent Water and Bassenthwaite Lake. Diagram adapted from Orr et al. (2004).

2.2.3 Historic channel change on the River Derwent

A study of historical channel changes on the River Derwent is useful in studying bank erosion, as large changes to the river channel course signify active bank erosion. A comparison of composite maps (modern Ordnance Survey data and the first edition of the County Series mapping (1863-7)) can be used to assess such changes (Figure 2.9). This suggests that the course and planform of the River Derwent has significantly changed in some reaches. Figure 2.9 shows the Derwent between How Farm (NY 247 243) and High Stock Bridge (NY 243 259), which suggests considerable change in channel location during the c. 120 years between the mappings. On the lower half of the map, the modern river between How Farm and Cast Rigg footbridge follows a course considerably to the east of its position on the original mapping. The river course is also much straighter than in the past, as the two sharp bends that once existed to the north-east of How Farm (approximate position: NY 248 244) are no longer in existence. On the northern half of Figure 2.9, the channel at the sharp meander (NY 246 253) has notably widened, and this meander bend has also become more acute. A similar broadening and shift in the channel has occurred at the next shallow meander downstream (NY 244 255). The Derwent has also changed its course considerably downstream of Low Stock Bridge. Significantly, the position of the Derwent's inflow to Bassenthwaite Lake has also changed. The river used to flow into the lake at the well-defined delta area at NY 229 272 following a westerly meander, however since the 1863-7 mapping the river has bypassed this delta, and instead follows an approximately straight channel into the south-west corner of the lake at Derwent Foot (NY 231 273).

Despite the change on these sections, the course of the Derwent in other areas has not moved significantly between the mappings. The position of the channel between the Derwent Water outflow and How Farm is very similar on both maps. However, the notable changes to channel course listed above imply active bank retreat and ongoing river bank erosion over time, and may explain the presence of actively eroding riverbanks today (Section 4.2).

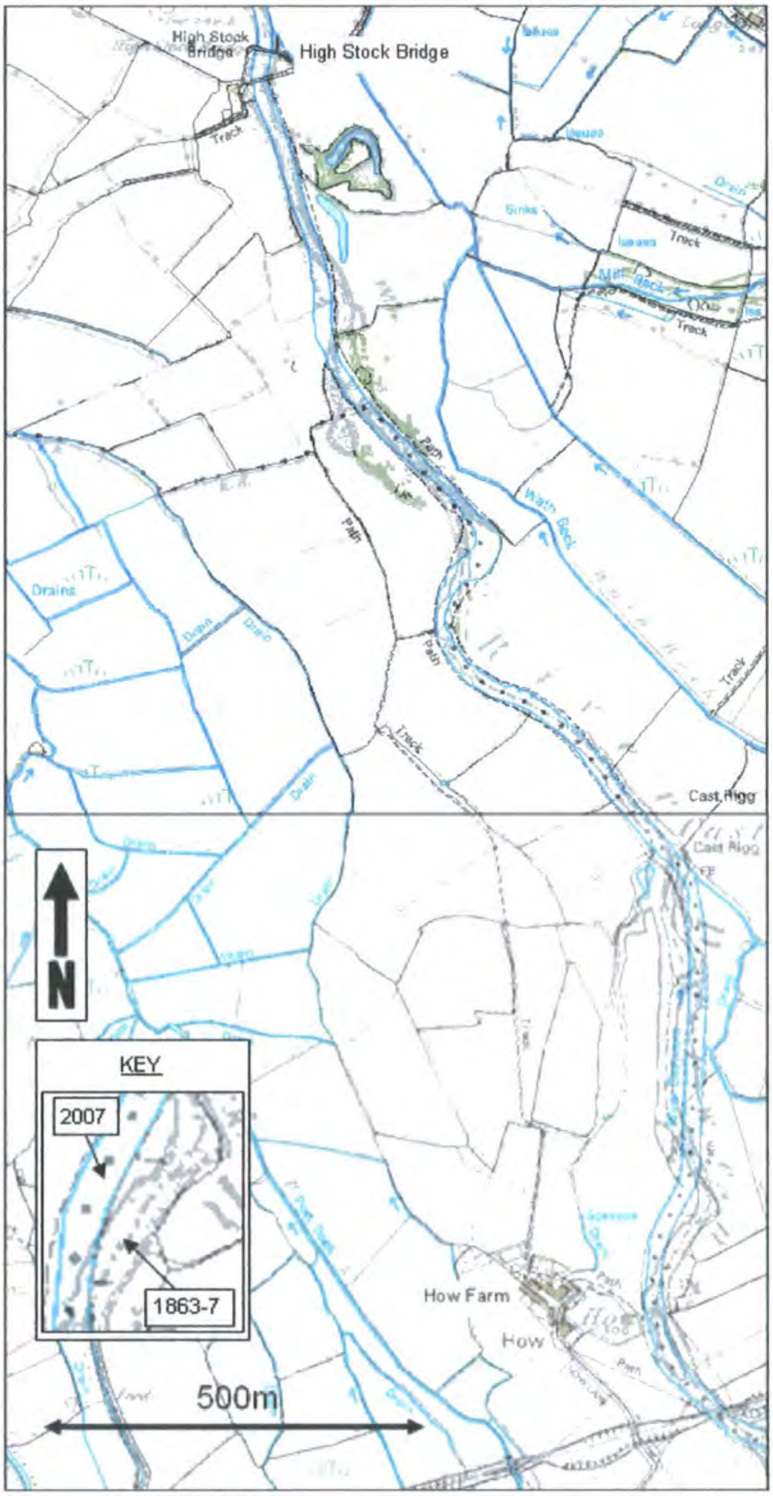

Figure 2.9: Channel changes on the River Derwent between How Farm and High Stock Bridge, indicated by an ArcMap overlay of County Series First Edition mapping (1863-7) and a modern National Grid map (2007).

2.3 Climate and sedimentation

The climate of a catchment, in particular the precipitation input, is an important factor influencing both suspended sediment transfers and the characteristics of the fluvial system (Figure 2.1). The erosion and transportation of sediment from hillslopes strongly depends on volumes of overland flow, and high river discharges contribute to increased stream power, which can transport larger volumes of suspended sediment and also lead to river bank erosion events. Bassenthwaite Lake has an upland maritime catchment, with typically cool and wet weather throughout the year. The close proximity of the Lake District to the Irish Sea, and associated prevailing south-westerly winds, favours high rainfall totals. Precipitation in the Bassenthwaite catchment varies greatly as a result of the orographic effects of the high central fells. This leads to average rainfall totals regularly in excess of 4,000 mm a^{-1} in the highest altitude areas in the south of the catchment, declining with decreasing altitude to just over 1,000 mm a^{-1} at Bassenthwaite Lake itself (Figure 2.10).

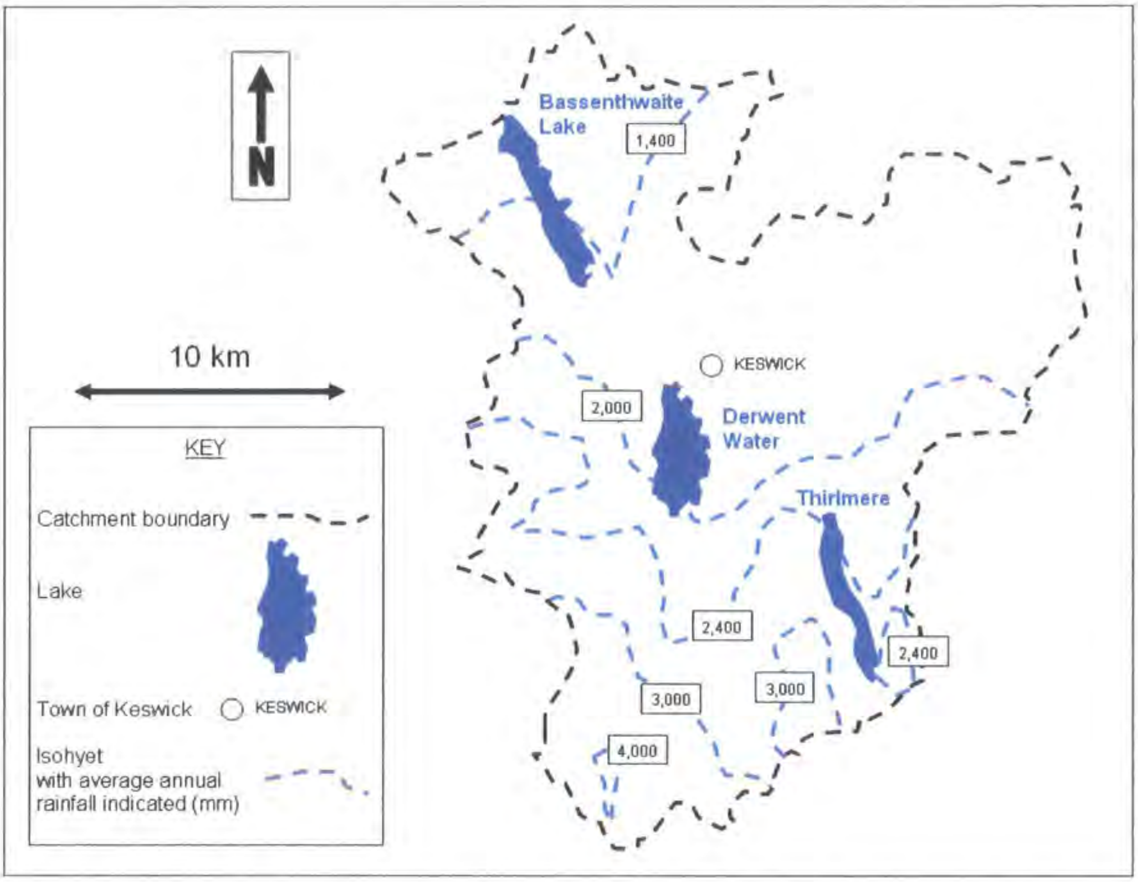

Figure 2.10: Mean annual rainfall distribution (1961-1990) in the Bassenthwaite Lake catchment, showing highest rainfall accumulations in the southern part of the catchment. Adapted from CEH (Crown Copyright 100017897), downloaded from http://www.nwl.ac.uk/ih/nrfa/spatialinfo/Rainfall/rainfall075003.html.

It is possible that precipitation, and associated river flows, are increasing in the Bassenthwaite catchment. Rain gauge records have been established in the Lake District from the mid-19th Century onwards, which suggest increases in annual rainfall totals at Dalehead and Sprinkling Tarn in the catchment uplands (Orr et al. 2004), and a notable increase in winter rainfall totals at Dalehead (although such trends feature high inter-annual variation) (Figure 2.11). Malby et al. (2007) have shown an increase in winter rainfall totals and rainfall intensities at higher altitudes in the Lake District during the latter part of the 20th Century, a trend reflected both in an increase in the frequency of high flow events in gauging stations in the Bassenthwaite Lake catchment (Orr et al. 2004) and nationwide trends of increasing precipitation intensities (Perry 2006, Maraun et al. 2008) and increasing river flows over the latter half of the 20th Century (e.g. Robson 2002).

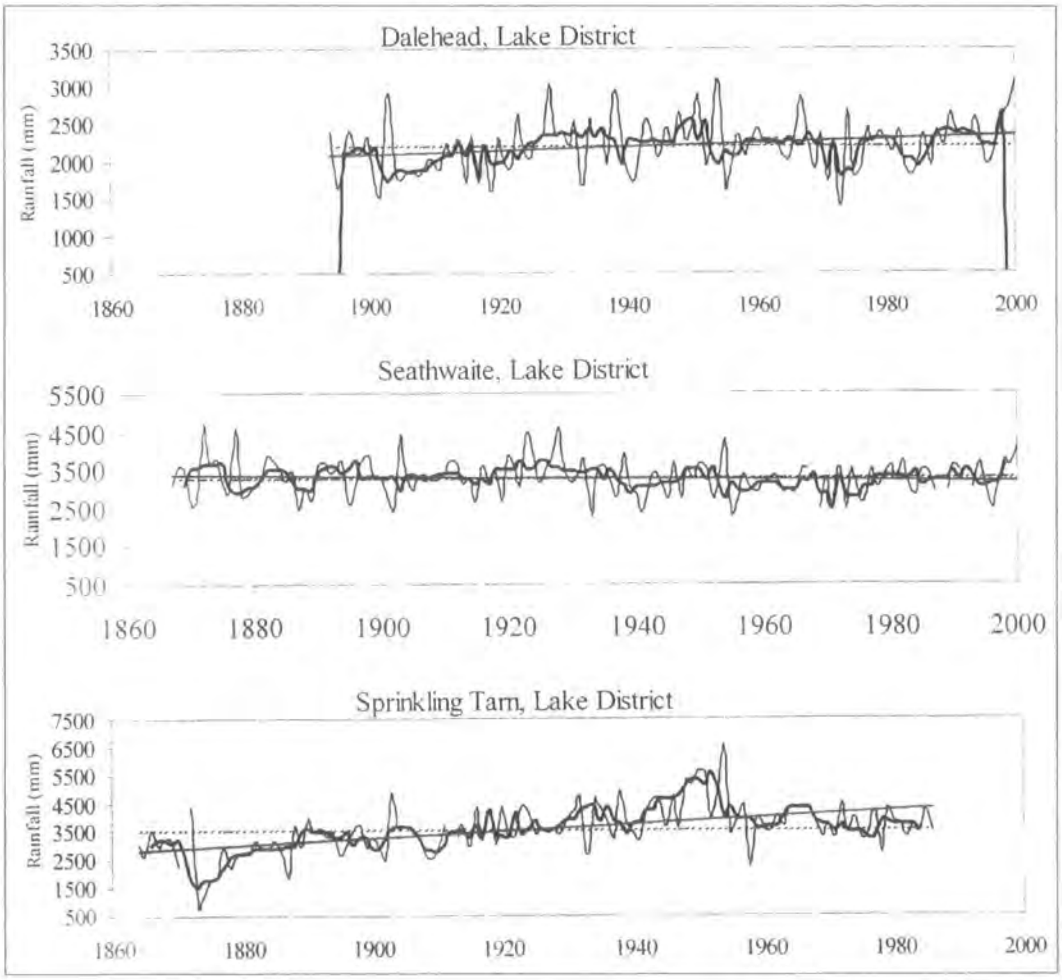

Figure 2.11: Rainfall totals at rain gauges in the Bassenthwaite catchment uplands over the past 150 years, with period trendlines highlighted. Adapted from Orr et al. (2004).

2.4 Assessment of river bank erosion

This section of the literature review outlines the literature on river bank erosion processes, the factors which influence bank erosion rates and the potential for river bank erosion to contribute to suspended sediment transfers.

In the Bassenthwaite Lake catchment, bank erosion of the Derwent lowlands has been suggested as an important source of fine sediment to the Lake (Orr et al. 2004, Section 2.2). This is due to its close proximity to the lake and the obvious linkage to the river channel network, especially when compared with more remote sediment sources in the catchment uplands. For the purposes of this study, the processes operating on the river banks on the River Derwent may be regarded as characteristic of those in a temperate river catchment. The hydrological and climatic factors which govern bank erosion processes vary spatially throughout the catchment and temporally over the course of a year. A good understanding of such processes is important in the analysis of sediment supply due to river bank erosion events, as they play a major role in determining the amount of sediment added to the system by bank erosion.

2.4.1 Definition and factors influencing river bank stability

River bank erosion is defined as the removal of material from river banks. Erosion occurs as a result of the actions of turbulent, high-velocity river flows which attack the river bank and cause the degradation and removal of bank material, either in the form of individual particles or larger blocks of material. The actual processes of bank erosion depend upon the structure of the bank and the type of materials present. In addition to the effects of the flow, the transport of sediment in the flow can cause erosion when it impacts the banks during high discharges.

Bank stability is generally affected by four sets of factors, which operate at different spatial scales (Figure 2.12). At the reach scale, the physical characteristics of the river bank (the type of material which composes the river bank and the morphology of the bank) are the main determinants of overall bank stability and the mechanism of river bank collapse. However, river banks are also susceptible to weakening by factors operating at larger scales. The local land use plays a major role in the delivery of material from the bank to the river, as it affects vegetation cover which can increase bank cohesion and stability. Finally, climatic factors (precipitation and temperature variations) contribute to both the physical strength of the river bank and the erosive power of the river channel.

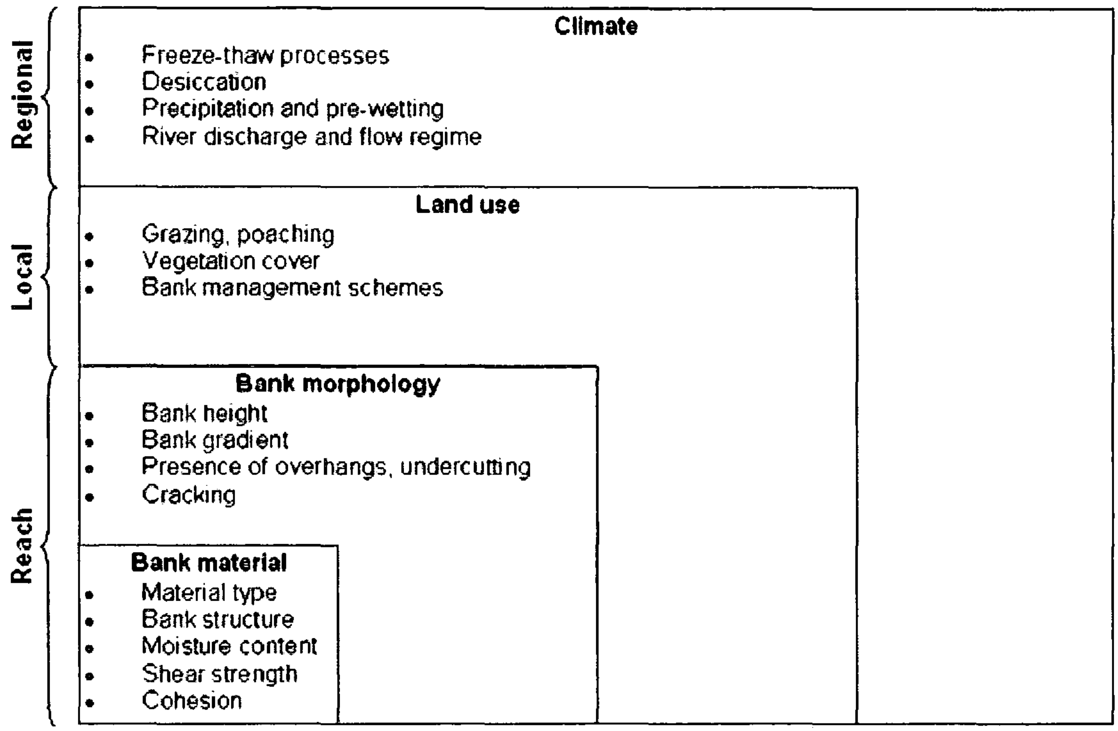

Figure 2.12: General factors affecting river bank stability. These operate at a range of scales, from the bank reach (bank material and morphology) to local and regional scales (land use and climate).

Many studies of bank stability have been reported in the literature (e.g. Schofield and Wroth 1968, Thompson 1970, Thorne et al. 1981, Simon and Hupp 1987, Simon et al. 2000, Dapporto et al. 2003, Rinaldi et al. 2004). In general, bank stability is the product of river bank morphology and bank material properties. Many studies suggest that bank failures become progressively more likely with increasing bank height and steeper bank gradients (Figure 2.13), which cause the factor of safety for a river bank to decrease (Lohnes and Handy 1968, Brunsden and Kesel 1973, Thorne 1982, Osman and Thorne 1988). Critical bank heights often vary with bank gradients and dimensionless factors of stability/safety can be calculated (e.g. Lohnes and Handy 1968, Thorne et al. 1981, Simon and Hupp 1987).

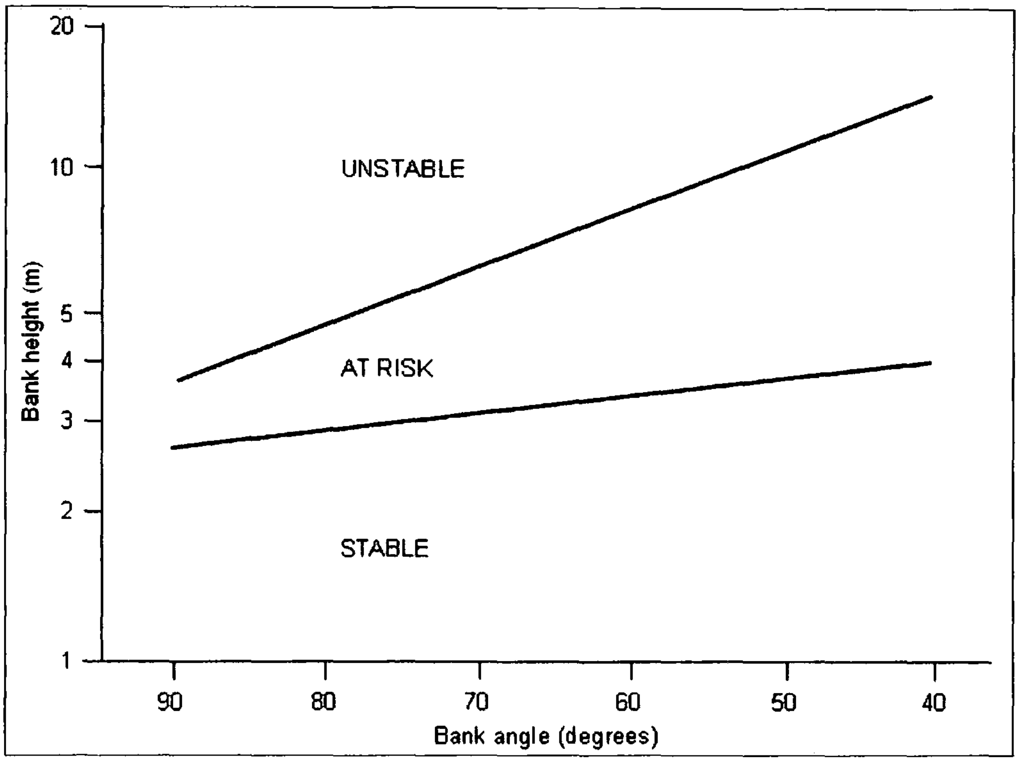

Figure 2.13: An example of slope-stability analyses, suggesting critical bank heights for river banks at certain angles. Adapted from Simon and Hupp (1987).

The role that bank material properties play in bank erosion is very important, especially the difference in erosion characteristics between cohesive and non-cohesive materials. Increased cohesion of bank materials, generally more prevalent in fine-grained materials with higher clay contents (Thorne 1978, Grissinger 1982, Osman and Thorne 1988, Thorne and Osman 1988), greatly changes dominant erosion mechanisms. For instance, non-cohesive materials are generally more liable to direct mechanical erosion by river flows (Hooke 1979), and are usually eroded as aggregates or individual particles. The erosion of such materials occurs as a result of forces acting on individual particles and the balance between motivating factors (weight, drag and lift forces) and resisting factors (friction and interlocking), as well as the mechanical properties of the material (angle of internal friction and packing density) (Hooke 1979).

When materials are more cohesive and bound together, the direct erosive actions of river flows are less effective (Thorne 1982). Processes which reduce the cohesive strength of the material, including climatic weakening and rises in pore-water pressures, lead to a loss of material strength, and often the erosion of large blocks of material (Thorne 1982).

River bank moisture contents (Section 2.4.4.3) and climate-influenced mechanisms of bank material preparation and weakening (Sections 2.4.4.1, 2.4.4.2) play an important role in bank stability. Rises in pore-water pressures following wetting of the river banks have been observed to increase the likelihood of bank failures due to reductions in shear stresses of bank materials (e.g. Darby and Thorne 1996, Dapporto et al. 2003, Rinaldi et al. 2004). The shear stress of any material is dependent on the overall cohesion of the material and the angle of friction (Taylor 1948, Lamb and Whittman 1969, Thorne 1982, Osman and Thorne 1988).

Fine sediment supply from river banks is determined by how active bank erosion events are at a river bank. Bank erosion activity itself is often determined by the concept of basal endpoint control (Thorne 1982, Lawler et al. 1997b). When river banks erode, sediment is delivered to the bank toe area and is removed over time at a rate dependent upon the erosive power of the river channel. If sediment is removed from the bank toe at a faster rate than it is delivered from the upper bank and fluvial deposition, then the lower bank is eroded and undercutting takes place, increasing bank angles and decreasing bank stability, and favouring bank failures and greater sediment inputs (**scour condition**). However if sediment is supplied to the bank toe at a greater rate than it is removed, accumulation of sediment occurs and decreases bank heights and angles, and buttressing the bank, leading to increased bank stability and lower sediment inputs (**accumulation condition**). In situations where sediment inputs and outputs to the bank toe balance each other out, then the river bank form remains similar and the bank form remains similar (**equilibrium condition**).

Although the morphology and geometry of the river bank play a major role in its stability, the land use at the river bank is also important to assessing bank erosion risks, as it influences the extent and density of vegetation cover at the bank. The presence of vegetation on a river bank usually increases its stability and reduces the susceptibility of the bank to flow erosion (Thorne 1990, Table 2.2), in turn reducing the risk of fine sediment addition to the river channel.

Reduction of erosion	Increased bank stability
• Decreases in near-bank flow velocities • Reduction of soil erodibility	• Improved bank drainage • Increased soil tensile strength • Slope buttressing • Increased surcharge weight

Table 2.2: A summary of the effects of vegetation upon river banks. Adapted from Thorne (1990).

The presence of vegetation on the riverbank reduces erosion by increasing the roughness of the near-bank area, therefore reducing the velocity and turbidity of flows and associated boundary shear stresses (Table 2.2). The presence of vegetation on a bank has been observed to increase erosion resistance by 1-2 orders of magnitude (Carson and Kirkby 1972, Kirkby and Morgan 1980), depending on root network density, vegetation re-colonisation rate, and vegetation extent down the bank (Thorne 1990). Vegetation also provides protection from rainsplash erosion, and increases soil cohesion due to the presence of roots. It also increases the infiltration capacity of the bank, reducing the volume of erosive surface run-off during storms.

Several studies of the influence of vegetation upon bank stability (e.g. Gray and Leiser 1982, Gray and MacDonald 1989) suggest that well-vegetated banks generally have lower moisture contents than banks with less vegetation. This is mostly due to interception and the uptake of moisture from the bank by the vegetation, as well as secondary evaporation from the bank surface. Additionally, well-vegetated banks are usually well drained, with a more open drainage structure provided by plant roots. This factor can increase hydraulic conductivity and reduce pore-water pressures, reducing in turn the risk of bank failure (Thorne 1990).

Roots and rhizomes also increase the tensile strength of soils and therefore their shear strength through binding. The presence of vegetation offers a ten-fold increase in tensile strength (Thorne et al. 1981) and large decreases in erosion rate (Smith 1976), although the presence of dead or decaying roots and tree stumps can have a negative influence on bank stability and can lead in some cases to soil piping (Thorne 1990). Generally, the roots produced by thick grass turf are more effective than the larger roots of trees and large shrubs) at promoting bank stability, a factor that has been noted in forested areas (Murgatroyd and Ternan 1983). The presence of buttressing roots near the bank toe also increases bank stability by checking low-angle soil slides in this area, and increasing roughness, lowering local flow velocities and encouraging bank accretion. Similar effects have been noted in areas of large woody debris accumulation (Simon and Hupp 1987). The addition of the surcharge weight of large vegetation (especially mature trees) can often have a negative influence on bank stability, especially as shearing and turning forces produced provide a likelihood of mass failures (Abam 1997a, b), although weight also increases resistance to shearing.

Vegetation has therefore been shown to have a generally positive net effect on bank stability, dependent upon vegetation type, density and spacing.

This is supported by field evidence of channel stabilisation following vegetation growth (e.g. Pizzuto and Meckelnburg 1989, Gurnell and Petts 2006). Reductions in vegetation cover therefore can have a negative influence upon bank stability, which in turn can lead to increased risk of bank failures and sediment addition.

2.4.2 Mechanisms of river bank failure

The two main mechanisms of river bank failure are cantilever failures - fluvial undercutting leads to the production of overhangs which then collapse into the channel, and rotational failures - mass slumping of bank material as a result of widespread loss of cohesion and strength. These failure mechanisms may be regarded as direct processes of river bank erosion, as they result from the erosive actions of the river channel. These mechanisms often cause large-scale failures on river banks, and are important as they can deliver large volumes of sediment to the river channel in a short period of time.

2.4.2.1 Cantilever failures

The key feature governing overhang-generated cantilever failures is a composite river bank structure (Figure 2.14). Typically, non-cohesive gravel deposits form the lower section of the bank (the remnants of former channel bars and other areas of deposition) while cohesive fine-grained sand/silt/clay deposits form the upper layer (overbank flow deposition). This bank structure favours high erosion rates of the non-cohesive lower bank, a function of the greater susceptibility of non-cohesive materials to fluvial entrainment and corrasion (Okagbue and Abam 1986, Simon et al. 2000, Section 2.4.1) as well as its greater exposure to river flows as a result of its lower elevation. Bathurst et al. (1979) suggested that during bankfull conditions, lower river banks typically experience higher water velocities and shear stresses, often leading to increased scour and undercutting. Similarly, fluctuating water levels and greater pre-wetting of such lower river banks further contribute to the erosion of the lower bank (Pizzuto 1984, Abam 1997a, b). Large variations in erosion rate across the bank face have been observed in many field studies, including those by Thorne (1978) and Thorne and Lewin (1978) of bank sections at Morfodion in Wales, where lower (non-cohesive) banks retreated by up to 600 mm in an 18-month period (average retreat rate = 200-350 mm), with a corresponding retreat of only 15-30 mm on the upper cohesive banks. The result of such undercutting is the production of overhangs, which is exacerbated by the effects of continued wetting and cracking (Thorne 1982). It is often the case that eroded material comes to rest at the foot of the bank, sometimes forming a talus cone or blocks of cohesive material from bank failures (Thorne and Lewin 1979). Cohesive blocks of material have been observed to break down gradually over time and form cohesive piedmonts at the bank foot which are can prove difficult to erode, as well as reducing bank gradients and can completely stabilise the bank (Brunsden and Kesel 1973, Thorne and Tovey 1981).

Figure 2.14: A well-developed, eroding composite river bank near Portinscale Bridge (height c. 2.5 m). Note the cohesive upper layer of fine-grained sandy material overlaying a non-cohesive lower layer of coarse pebbles and gravel. The turf slippage and slight overhang development at the bank top, and the steepened profile of the lower bank suggest recent active erosion of this bank.

The overhang continues to develop until an equilibrium state is met, generally as a result of the increasing width of the cantilever. At this point the tensile strength of the block is exceeded by the increasing width and the block topples forward into the channel. This is the most basic form of cantilever failure and is known as a beam failure (Figure 2.15). The characteristic failed blocks are the best identifying characteristic of this failure type (Pizzuto 1984).

The development of tension cracks in the cohesive overhang plays a major role in supplying material to the channel. Steep bank angles lead to gravity-induced cracks (Abam 1997a, b), and occur where tensile stress due to the weight of the block overcomes the tensile strength of the soil (Thorne and Tovey 1991). Abam (1997b) has provided a factor of safety analysis for such blocks and has proposed a critical block width, above which tension cracks would be expected to occur. Such tensile failures result in the lower part of the block falling into the channel (Figure 2.15). The third type of cantilever failure is known as a shear failure, where the overhanging block shears away from the bank face along a vertical shear plane. Such failures occur when the shear stress acting on the shear plane as a result of the (increasing) weight of the overhanging block exceeds the shear strength of the soil on that shear plane (Figure 2.15). Differences in the type of cantilever failure occurring on a bank are the product of differences in bank geometry and materials (Thorne and Lewin 1979, Abam 2001).

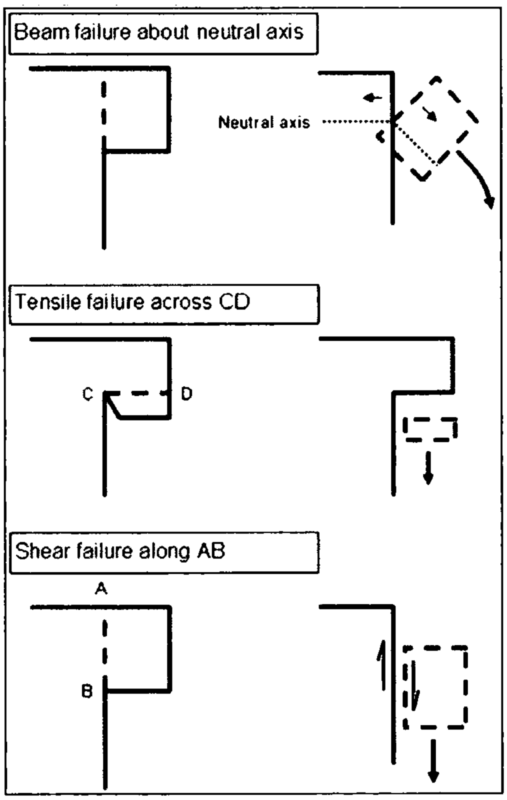

Figure 2.15: Mechanisms of cantilever failure: beam failure, tensile failure and shear failure. Adapted from Thorne and Tovey (1981).

Cantilever block failures are extremely significant in sediment supply, as they occur suddenly and transfer a large volume of sediment to the river channel. Failed blocks of material from the upper bank resting at the foot of the river bank are the key indicator of this form of erosion. Although analyses have been produced to assess the risk of cantilever failures for eroded river banks (e.g. van Eerdt 1985, Abam 2001), as a general rule cantilever failures are encouraged by steep river bank gradients and an undermined upper bank.

2.4.2.2 Rotational failures

Rotational failures of river banks differ from cantilever failures as described above, as the failure does not result from instabilities generated by changes in bank morphology (oversteepening and undercutting) but a widespread weakening of the materials in the river bank, which causes large-scale slumping and mass failure. As the failure mechanism is dependent upon the properties and weaknesses of cohesive materials (Section 2.4.1), the largest failures of this type are found in cohesive bank reaches. However, in composite banks where cohesive materials overlay coarser, non-cohesive materials, rotational failures regularly occur in the cohesive upper bank, as the interface between the two materials can act as a base for failure and plane of weakness (Thorne 1982). In this case, rotational failures have been observed to occur alongside cantilever/block failures (Brunsden and Kesel 1973). Like cantilever failures, rotational failures are very important in sediment supply to river channels, as they involve the erosion of large volumes of sediment in a short period of time.

Rotational slumping most often occurs as a result of a loss of shear strength in the river bank, normally as a result of increased water contents (Hooke 1979). Whenever water drains into a river bank following river level rise or precipitation, pore-water pressure rise, accompanied by reductions in shear strength, and increases in lubrication along potential failure surfaces (Simon 1989, Simon et al. 2000). The weakening of river banks by pre-wetting is discussed below (Section 2.4.4.3). Failures tend to occur as deep-seated slumps, with a curved failure surface located well within the river bank, leading to some backwards rotation of the failed material (Thorne 1982, Harris 2003). Rotational slumping is also favoured by increases in bank weight as a result of the higher water content of the bank following wetting, as well as seepage and piping forces and the presence of tension cracks (Bradford and Piest 1977). Rotational failures are usually observed in the field as masses of slumped material, which often rest at the foot of the river bank in lobate/flow forms (Simon 1989).

However, not all rotational failures are deep-seated, and smaller 'slip' failures often exist on cohesive river banks (Dapporto et al. 2003, Figure 2.16). These smaller failures often occur when river banks and cohesive layers are low (Sullivan 1972). Although the extent of such individual slips is relatively small, high frequencies of slip failures can add a substantial amount of material to the channel (Thorne 1982). The majority of such slips occur as a result of tensile stresses in the upper bank (Terzaghi 1943), which often arise as a result of removal of overburden pressure due to slope excavation or stream erosion (Thorne 1982), which causes tension cracks to form in the river bank (Figure 2.16). Water flows in such cracks weakens the block's effective cohesion, eventually causing shallow slips. The likelihood of such slips generally increases with higher and steeper river banks, which increase the tension stresses responsible for such failures.

Figure 2.16: Shallow slip failure on the river bank of St. John's Beck, St. John's-in-the-Vale, Cumbria. The failed block has not been further eroded and it remains well vegetated. An obvious tension crack (indicated by the white arrows) is situated between the failed block and the retreated bank face.

2.4.3 Draw-down failures

Several studies have observed a tendency for river bank failures to occur after, rather than during, flood events. This has been noted by simple field observations. For example, Twidale (1964) noted the frequent presence of slumped debris at the foot of channel banks, and suggested that it must have been formed during the receding/recessional limb after the flood peak, as otherwise it would have been washed away. Similar observations have been made by Okagbue and Abam (1986), Simon and Hupp (1987) and Thorne (1990). Simon et al. (2000) suggest that rapid drawdown is a major conditioning factor on river bank erosion. The phenomenon of 'draw-down' failures, where bank erosion occurs after the flood peak, was therefore postulated. The most likely explanation for such failures is the fact that high water flows maintain a supporting, buttressing effect on river banks; after the river level descends, this is removed and the heavy, thoroughly pre-wetted banks collapse into the channel. This is the mechanism proposed by Lawler et al. (1997a) to explain several 'delayed' bank erosion events in Wales, where river bank erosion events were observed to occur well after the passing of flood peaks. Draw-down failures are supported by factor of safety analyses (e.g. Koppejan et al. 1948, Morgenstern 1963) which suggest that bank materials become susceptible to erosion on the recessional limb. Such failures play an important role in causing temporal variations in sediment supply.

2.4.4 River bank weakening processes

Although river bank erosion primarily occurs due to the actions of the river channel, such processes are more effective if the river bank materials are in a weakened state. Weakening can occur by a range of processes, but bank materials are especially susceptible to reduction in strength by climatic factors (temperature and soil moisture). Therefore, the risk of bank erosion and sediment addition is increased when such processes are operating on the bank. There are three main processes which are relevant to river banks in temperate climates such as north-west England.

- freeze-thaw weathering
- desiccation
- pre-wetting

Freeze-thaw and dessication processes occur as a result of variations in temperature and lead to the production of loosened aggregates that are entrained more easily than if the sediment was not weakened. Pre-wetting of river banks occurs following rainfall and high river flows, and is especially important in reducing bank stability, particularly regarding weight changes and increases in pore-water pressures. Such processes may be regarded as indirect processes of river bank erosion, as they do not result from direct erosion by the river channel but through atmospheric processes.

2.4.4.1 Freeze-thaw weathering

Freeze-thaw weathering is an umbrella term used to describe a range of processes that bring about the weakening and breakdown of materials as a result of the actions of frost and ground freezing. Freeze-thaw and associated needle-ice processes are common during the UK winter, as temperatures regularly drop below 0 °C (Lawler 1988). In UK rivers, freeze-thaw is a relatively weak process of direct erosion. A study on the River Ilston (South Wales) of the direct measurement of freeze-thaw debris accumulations suggested that it only contributed 9% of the total amount of bank erosion (Lawler 1987). Freeze-thaw generally acts independently of fluvial activity (Twidale 1964, Lawler et al. 1997b); however, the main effect of the process is to loosen bank aggregates and increase the susceptibility of the bank surface to erosion (Knighton 1973, Thorne and Lewin 1979). Freeze-thaw is therefore especially effective when combined with high, powerful river discharges and pre-wetted river banks (Lawler 1987, Figure 2.17), and when this occurs the weakened river bank is susceptible to large-scale failures and the delivery of large volumes of sediment to the river channel can occur.

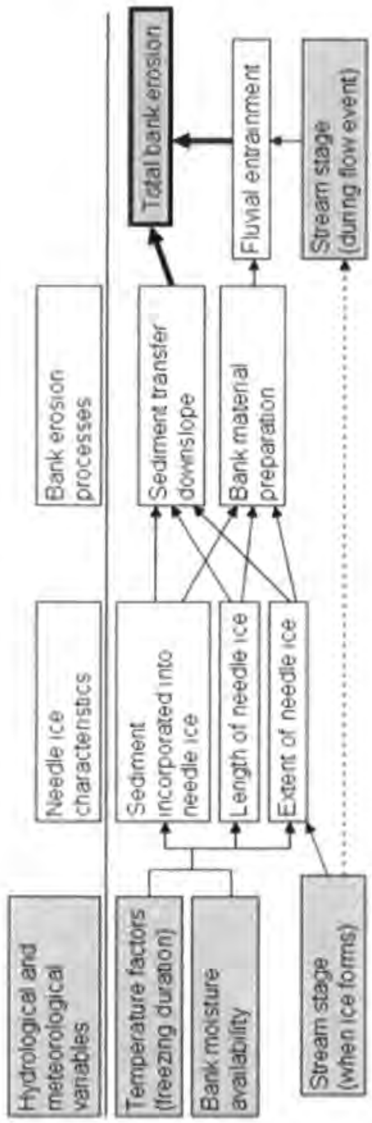

Figure 2.17: A flow diagram showing the role of needle ice in producing bank erosion, emphasising the importance of hydrological and meteorological variables in needle ice formation and subsequent bank erosion processes. Adapted from Lawler (1987).

In models of spatial variation in dominant bank erosion processes (Lawler 1992, 1995, Lawler et al. 1997a, 1999), freeze-thaw erosion is shown to decrease in occurrence downstream. This is a function of decreasing altitude and increased temperatures and smaller temperature ranges. In temperate climates such as Bassenthwaite, needle-ice is likely to be dominant in small upland catchments where it can provide a significant proportion of total erosion (Lawler 1992).

Needle ice, a common form of freeze-thaw processes in temperate climates, is defined as "the accumulation of slender, bristle-like ice crystals practically at, or immediately beneath, the surface of the ground" (Washburn 1979, Figure 2.18). Such crystals grow in the direction of nocturnal cooling (Lawler 1988) and can reach up to 80-100 mm in length over longer periods of freezing (Outcalt 1971), though more typically 20-50 mm long needles which develop during daily frost cycles (e.g. Lawler 1986). Field research suggests that soil and till structures are important in determining the extent of needle ice development, with larger-grained tills having large pore spaces which facilitate needle ice formation (Hill 1973). During needle-ice events, sediment is incorporated into ice crystals when the freezing front descends into the bank. Sediment is transported down the bank during thawing by a range of falling, meltwater, sliding and toppling mechanisms (Hill 1973, Lawler 1993). Increased sediment content of the ice has been shown to cause increased stresses and further weakening of the bank surface, especially when the bank is fairly dry or cooling rates are high (Lawler 1993). After needle ice action, materials are notably 'crumbly' in texture, and a loose 'skin' forms on surfaces with a low packing density that is readily entrained by river flows (Lawler 1986, 1993, 1999, McGreal and Gardiner 1983). After such material is removed, small erosional notches at past river flow levels are often present (Wolman 1959, Leopold 1973, Lawler 1993).

Figure 2.18: Needle ice observed on bare in the upland Bassenthwaite catchment on 26th December 2006. The crystals in the photograph were around 50 mm in length.

Freeze-thaw processes play an important role in bank erosion. Lawler (1995) researched climatic conditions at sites on meander bends in South Wales, and observed very strong (coefficient>0.9) correlations between mean and maximum bank erosion and the duration of air temperatures below 0 °C. As a mechanism of sediment delivery to the river channel, needle ice is most effective when it is accompanied by high and erosive peak discharges capable of transporting large amounts of weakened material. Also, when banks are pre-wetted (after a period of rain or high river levels), needle ice growth is often widespread due to the greater source of moisture. Wolman (1959) suggested that the second most erosive flow type (after high flows on pre-wetted banks) was moderate stage rises after or during needle ice events. Lawler (1993) also observed a tendency for needle ice events to occur at freezing temperatures with a high antecedent precipitation index (Gregory and Walling 1973). Overall models of bank erosion have suggested the importance of these factors, and it is the coincidence of cold temperatures, high precipitation and large river discharges during winter that lead to the dominance of bank erosion events at that time of year (Lawler 1987, 1993) (Figure 2.17).

2.4.4.2 Desiccation

Desiccation is defined as the weakening of a material due to a deficit of moisture. Its role in the erosion of upland peat is well-documented (e.g. Francis and Taylor 1989), however its part in river bank erosion is more uncertain. For instance, Thorne (1982) states that "Hard, dry banks are highly resistant (to erosion)" (when compared to a pre-wetted bank), while field observations in Wales have noted the collapse of fine-grained material on river banks during drought conditions (Oxley 1974) and widespread cracking of banks during summer in Australia (Bello et al. 1978). A lack of river bank temperature datasets makes the role of desiccation difficult to quantify (Lawler et al. 1997b), but it is postulated that it plays a role similar to that of freeze-thaw processes.

In temperate catchments such as that of Bassenthwaite Lake, it is difficult to quantify the occurrence of high bank temperatures required to cause desiccation, although the process has been observed (Figure 2.19). In hot and arid climates the role of desiccation in cracking is not in doubt (Abam 1997a, b). However, data from southern England indicates that soil temperatures can reach in excess of 30 °C (and occasionally 35 °C) during exceptionally hot summers, and rises in temperatures of 7 °C per hour during morning heating (Lawler 1992). In this study (of the River Arrow in Worcestershire), bank surfaces became strongly desiccated with observations widespread cracking and exfoliation, with mini-talus slopes forming at the bank foot. Bank freezing can also lead to desiccation if a strong moisture gradient forms in the bank. Dramatic changes can result from exfoliating processes in particular which can drastically weaken bank surfaces. Desiccation needs to combine rises in river stage to erode away weakened materials for it to be considered an effective process of bank erosion, and it is therefore similar to freeze-thaw and pre-wetting in that respect.

Figure 2.19: A desiccated river bank on the River Derwent near Bassenthwaite Lake, showing a dry and crumbly upper bank with deep cracks in the upper bank surface.

2.4.4.3 Pre-wetting

Pre-wetting is defined as the increase in bank water content as a result of river level rise or precipitation before the main flow event has taken place. It plays an important role in weakening banks, often in conjunction with freeze-thaw and other weakening processes. The extent to which banks become saturated is largely dependent upon the effectiveness of bank drainage and the duration of the supply of water. The intensity and duration of rainfall events are the most important characteristics in producing wetting of river banks (Gregory and Walling 1973).

Many early engineering studies have observed the decrease in strength in soils following increases in water content (e.g. Trask 1959, Sharp 1977), particularly in cohesive materials. With low water contents present, pore-water pressures are negative and pore-water suction gives river banks an apparent cohesion, which is important especially in increasing strength in banks made of non-cohesive materials (Thorne 1982). Strength is reduced in wetted banks as a result of an increase in positive pore water pressure, which in turn causes a reduction in the bank's effective strength (Thorne 1982). Especially high pressures force soil units apart, increasing friction angles and reducing the cohesion of bank materials. Many studies have suggested critical factors of safety regarding pore-water pressures for banks of certain heights (e.g. Dapporto et al. 2003, Rinaldi et al. 2004). Pre-wetting also results in a large gain in the bank's unit weight through the increase in water content, and this is especially important in promoting 'draw-down' failures after the flood peak has passed, and the buttressing effect of the high river levels is removed. Simon et al. (2000) suggests that prolonged rainfall causes five destabilising effects upon a river bank: an increase in bulk unit weight, a loss of apparent cohesion, the generation of positive pore-water pressures and therefore a loss of frictional strength, a loss of confining pressure, and the entrainment of failed material at the bank toe.

2.4.5 Temporal variations in river bank erosion

Many studies have observed that river bank erosion and retreat events are not distributed evenly throughout the year, and strong temporal trends are present in erosion rates (Table 2.3, Figure 2.20). The climatic and hydrological factors that promote these differences in temperate climates are discussed below.

Study reference	Location	Findings
Hill 1973	Northern Ireland, UK	75-90% of annual bank retreat from October-January.
Hughes 1977	Shropshire, UK	Mean loss of material highest during winter.
Thorne and Lewin 1979	Wales, UK	Clear winter peak in bank retreat rates (River Severn): November-April – 30 mm a^{-1} June-October – 12 mm a^{-1}
Lawler 1986	Wales, UK	(Figure 2.20)
Wolman 1959	Maryland, USA	85% of observed bank erosion during winter months (December-March)
Twidale 1964	Adelaide, Australia	Winter retreat at study site – 624 mm Summer retreat at study site – 16 mm

Table 2.3: The strong seasonality of river bank erosion, suggested by the findings of four key UK studies and two studies from the USA and Australia.

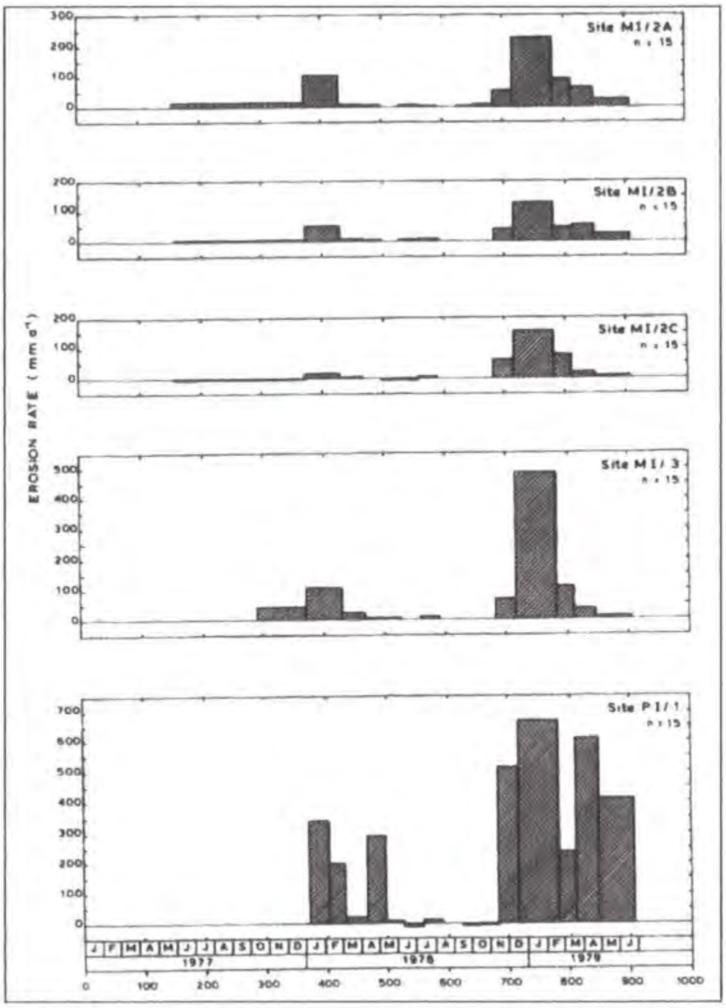

Figure 2.20: Bank erosion rates on river banks on sites in South Wales in a study period from 1977-1979, showing a strong seasonality of erosion rates. Diagram from Lawler (1985).

Temporal variations in bank erosion over the course of a year are the product of variations in precipitation (and associated river stage) as well as a range of other variables and processes that influence bank stability (Lawler 1992). These include patterns of river flows and their influence on both direct erosion of banks and bank moisture contents, as well as bank weakening processes and vegetation cover. The main cause of enhanced bank erosion in the temperate winters and early spring periods is the peak in precipitation values at this time. In the British Isles, cyclonic weather conditions tends to dominate at this time, which are exacerbated in the Lake District by orographic effects leading to extremely high precipitation totals (Section 2.3). Wilby et al. (1997) argued that 62% of the variance of historical sediment yields can be explained by the ratio of cyclonic:anticyclonic conditions. Cyclonic conditions yield high rainfall intensities, longer storm durations and a higher number of extreme events. There is evidence that the duration rather than the intensity or volume of rainfall is the key factor in producing bank erosion, due to its effects on pre-wetting of river banks. Knighton (1973) carried out research in Cheshire which suggested that complex, multi-peaked storms featuring high, oscillating discharges were more effective at eroding river banks than single-peak events. Similarly, Thorne and Lewin (1979) emphasised the effectiveness of a high frequency of small floods in producing bank and channel erosion, rather than occasional large floods. Many studies have observed the importance of intermediate, fluctuating flows that occur several times a year in causing bank retreat (Wolman and Brush 1961, Harvey 1975, Hooke 1980) and they play a role especially in eroding the lower bank and so undercutting (Knighton 1973). Therefore, a strong connection is present between climate, river regime and bank erosion patterns.

Furthermore, the importance of freeze-thaw processes in preparing bank material for erosion has been noted. The dominance of needle ice events in winter (although such processes do not always coincide with peak discharges), leads to the production of weakened aggregates that are readily entrained in low to moderate flows. Lawler's extensive research on bank erosion (Lawler 1986, 1987, 1993) identifies freeze-thaw as an important contributing factor to temporal variations in erosion. Hill (1973) observed widespread frost action in two Northern Irish catchments, and supported its role in producing the 75-90% of annual bank erosion which occurred between October and January. Other surveys point to pre-wetting as the main factor in bank retreat, while Thorne (1990) suggests that the decline in vegetation cover in winter reduces cohesion and bank protection; conversely the presence of vegetation also reduces sediment transfer in summer due to the increased bank stability (e.g. Lawler 1992). In summary, the dominance of bank erosion in the winter and early spring is a result of high, erosive discharges caused by high precipitation totals, and the presence of weakened, erodible banks as a result of pre-wetting, freeze-thaw processes and a decreased overall vegetation cover. The strong temporal trend in bank erosion events is also reflected in patterns of suspended sediment delivery, which are highly episodic in nature (e.g. Thompson and Oldfield 1986, Walling and Webb 1987) largely as a result of higher river flows during winter.

2.4.6 River bank erosion and sediment budgets

The proportion of sediment supplied to a catchment by river bank erosion varies greatly between river catchments (Table 2.4). The differences in bank erosion contributions to sediment budgets observed between catchments are the result of differences in bank properties, river channel dynamics and land use patterns.

Reference	Study location	% of total sediment load from bank erosion
Russell et al. 2001	South Wales, UK	<10
Bull 1997	River Severn, UK	17
Ashbridge 1995	River Culm, UK	19
Nelson and Booth 2002	Issaquah Creek, USA	20
Odgaard 1987	Iowa, USA	30-40
Walling et al. 1999	River Ouse, UK	37
Lawler et al. 1999	River Ouse, UK	37
Sekely et al. 2002	Blue Earth River, USA	37
Wilkin and Hebel 1982	Illinois, USA	50
Duijsings 1987	Luxembourg	53
Rondeau et al. 2000	St. Lawrence River, Canada	65*
Imeson et al. 1984	Luxembourg	>80
Kronvang et al. 1997	Denmark	92*

*Table 2.4: The varying contributions of river bank erosion towards sediment budgets in studies from the UK and across the world. * - percentage includes bed scour.*

High sediment yields from bank erosion (either at the reach or the catchment scale) suggest that the river channel is unstable in its behaviour. This is often as a result of a favourable river regime (especially a 'flashy' response to precipitation events), active channel morphological changes and channel migration, and/or the presence of easily-eroded bank sediments. For instance, Walling et al. (1999) observed well-developed, high (>2 m) river banks on the River Ouse from which sediment could be readily entrained during high discharges. This was a key factor in the high (37%) bank erosion contribution to the sediment budget of that river. Duijsings' (1987) sediment budget for a small upland stream in Luxembourg suggested a high proportion of sediment (53% of total load) is sourced from river banks, the majority of which was removed from the bank by corrosion and soil fall as a result of continual active channel incision.

Similarly, a very high proportion of sediment in upland British Columbian catchments (Canada) is sourced from bank erosion as a result of the presence of massive quantities of glacial sediment and debris in river banks and bluffs in upland areas. The high sediment flux from these sources reflects the fluvial system's long-term adjustment to the glacial era of 10 k a^{-1} ago (Church and Slaymaker 1989). A similar response to past glaciation has been noted in the St. Lawrence River (Canada) sediment budget, where large volumes of alluvial deposits are being cut through (Rondeau et al. 2000), enhanced by a high discharge flow regime and anthropogenic disturbances (including ship generated waves, wind-enhanced turbulent currents and bank modifications). Largely unmodified upland catchments often feature high bank erosion contributions to sediment budgets, as absence of agricultural land (except non-intensive grazing) greatly reduces the extent of surface erosion and material sourced from field drains and surface-run off.

In some catchments, other sources of sediment may be predominant in the sediment budget. This has been observed in river basins where a particular land use (especially intensive agriculture) covers much of the land area, an effect exacerbated in smaller catchments. Russell et al. (2001) used source fingerprinting techniques in two small (area<4 km^2) catchments in southern Wales and noted a minimal contribution of bank erosion towards the sediment budget (<10% of total sediment yield). He attributed this to the dominant agricultural land use in the catchments, leading to the largest sediment sources being field drains (30-55% of total sediment yield) and surface erosion (34-65%). Similarly, a rapidly-urbanising watershed in Washington, USA (Issaquah Creek) had a sediment budget with high proportions of sediment from landslides in building areas (50%) and road-surface run-off (15%) compared with the bank erosion contribution (20%) (Nelson and Booth 2002). It is often the case that bank erosion can dominate sediment supply at local reach scales, but it is often superseded by other sources at the catchment scale (Bull 1997).

2.4.7 Spatial variations in river bank erosion

While river bank erosion occurs throughout a catchment, the processes involved to produce bank erosion vary throughout the system. Lawler (1985) has suggested that the processes which cause and contribute to bank erosion change throughout the river system. This is because the relative importance of bank weakening processes, stream power and bank morphology change throughout the river system.

Processes of sub-aerial preparation (especially freeze-thaw) tend to dominate in the upper catchment and decline in importance downstream. In the case of freeze-thaw, temperatures are typically lower in higher-altitude uplands so needle ice can develop readily, more so than in lowland catchments.

Direct processes of fluvial entrainment (the erosion of material by the action of the river water rather than mechanical failure of the bank) are related to boundary shear stresses in the channel, which vary with stream power. Field observations suggest that stream power peaks in the mid-basin river reaches, and that stream power is lower upstream (due to smaller discharges) and also lower in downstream reaches (due to lower channel gradients) (Lewin 1982). However, stream power in extreme floods has been shown to vary greatly (Bull 1979, Magilligan 1992). The phenomenon of a mid basin peak in stream power has been observed on the River Severn where mid-basin reaches have the greatest channel mobility (Lewin 1987) and a similar trend in bank erosion dominating in middle reaches was found on the rivers Swale, Ouse and Ure (Lawler et al. 1999). Research in arid climates has also supported the mid-basin peak hypothesis (Graf 1983). Therefore in middle reaches of river basins, a majority of bank erosion might be expected to occur as a result of the erosive power of river flows.

Mass failures of river banks (the delivery to the channel of large amounts of material) have been discussed in river bank stability analyses (Section 2.4.1). The key component of these analyses is the factor of safety for slopes, whereby the properties of a river bank (slope gradient, mechanical properties, pore-water pressures, type of material) contribute to an overall criterion of bank stability. A critical bank height can be calculated, above which bank failure can occur. As bank heights typically increase downstream (e.g. Leopold and Maddock 1953, Prestegaard 1988), it can be postulated that a section of river banks will exist where bank heights exceed critical values and therefore mass failures will be the dominant process of bank erosion. Upstream of the lower reaches, the banks are too low for mass failures, and therefore bank erosion is dominated by other processes.

The result is a series of "overlapping process domains" (Kirkby 1980) where different processes and mechanisms dominate bank erosion at different points in the channel network based on variations in climate, flow characteristics and changes in bank strength and resistance to erosion (Figure 2.21). The increasing likelihood of mass failures in lowland areas suggested by this model supports field observations of river bank erosion on the lowland River Derwent (Section 2.2), and the high potential for it to contribute to suspended sediment delivery to Bassenthwaite Lake.

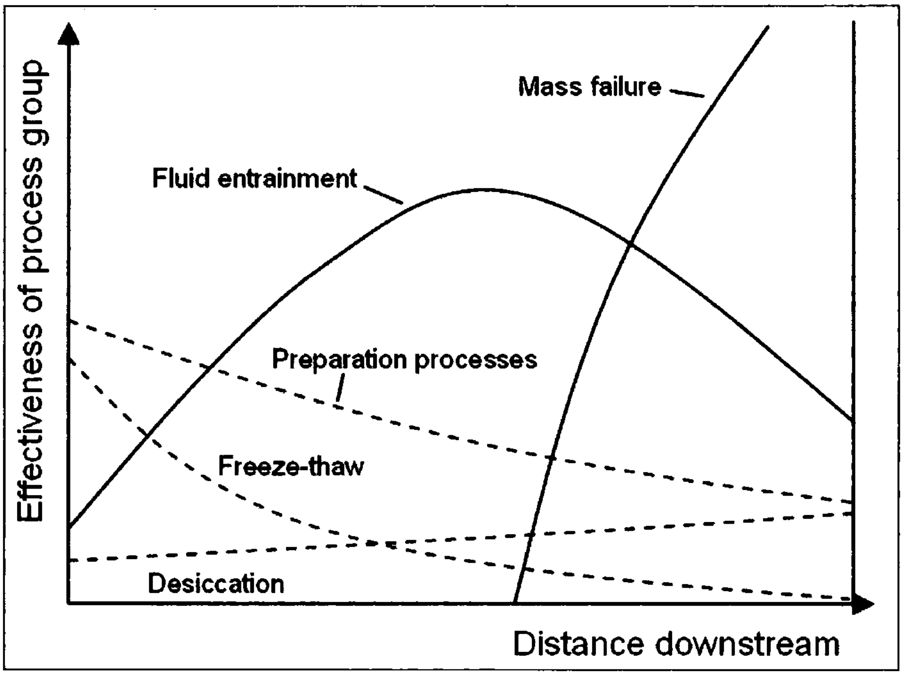

Figure 2.21: The distribution of dominant bank erosion processes along a hypothetical river system, showing a transition from the dominance of preparation processes (especially freeze-thaw) in the uplands of a catchment to fluid entrainment processes and mass bank failures at lower river reaches. Adapted from Kirkby (1980).

2.5 Literature review summary

Suspended sediment transfer in a large catchment such as that of Bassenthwaite Lake is clearly a complex process involving inputs from several sources. However, previous studies have shown extensive river bank erosion in the catchment, particularly on the River Derwent between Derwent Water and Bassenthwaite Lake (Section 2.2). The direct linkages that eroding river banks have with the fluvial network, particularly in comparison to remote sources of sediment on hillslopes, suggest that river bank erosion is a key component of the catchment's sediment budget. Furthermore, sediment supply from river bank erosion is governed by several factors and processes which influence the river bank. At a given river bank, morphology and material composition are the two key factors controlling the risk of bank erosion events and sediment addition to the river channel, with land use and climate further influences on the river bank. Increases in bank height, gradient and undercutting increase the risk of large failures, including block failures, which have the potential to deliver considerable volumes of fine sediment to the river channel. At the annual scale, the majority of river bank erosion over the course of the year occurs during a small number of high magnitude failures, usually during winter, which is exacerbated in temperate catchments such as that of Bassenthwaite Lake by a wet climate and associated high river discharges. Active river bank erosion has the potential to deliver a significant proportion of a catchment's sediment budget (Section 2.4.6) which makes large river bank failures particularly important.

The literature review reinforces the importance of measuring and quantifying suspended sediment transfer characteristics and the extent of river bank erosion in the Bassenthwaite Lake lowland catchment, in order to answer the research questions described in the introduction to this thesis (Section 1.6). Therefore, the methodology (Chapter 3) describes two sets of field techniques, the first being data collection relating to suspended sediment transfers on the River Derwent and Newlands Beck, and the second being an assessment of river bank erosion on the River Derwent.

CHAPTER THREE

METHODOLOGY AND FIELD TECHNIQUES

This chapter describes the methods and techniques used to collect data on suspended sediment transfers and river bank erosion in the Bassenthwaite Lake catchment. The fieldwork that has taken place during this project has been directed towards two key areas. The first was a study of suspended sediment transfers in the catchment, which was used to assess the sediment transfers to Bassenthwaite Lake from the River Derwent and Newlands Beck as well as the overall catchment sediment budget (inputs, outputs and lake sediment storage). This has been carried out by data collection at four monitoring stations. The second task was a related study of river bank erosion on the lowland River Derwent between Derwent Water and Bassenthwaite Lake which aimed to assess the potential significance of river bank erosion as a source of fine sediment within the catchment sediment budget. This was done by mapping the extent of bank erosion, and a preliminary survey of bank morphological changes on a reach of the River Derwent using a terrestrial laser scanner.

3.1 Field monitoring stations

In order to assess patterns of suspended sediment delivery in the Bassenthwaite Lake lowland catchment, the most useful approach is to use a basic sediment budget model, thus:

Inputs = Outputs + Δ Storage *(Equation 3.1)*

As the main ecological problems of Bassenthwaite Lake are caused by fine sediment accumulation (Section 1.3), it was important to quantify the suspended sediment transfers to Bassenthwaite Lake as well as the overall sediment budget of the lowland catchment (Figure 3.1, Equation 3.1). In order to do so, four monitoring stations have been established on the rivers around Bassenthwaite Lake (Figure 3.2, 3.3). Three of these stations were installed to monitor the suspended sediment inputs to Bassenthwaite Lake. On the River Derwent, two stations were installed at Portinscale and Low Stock Bridge. The Portinscale station was located to monitor suspended sediment inputs from the upland catchment of the River Derwent. The station at Low Stock Bridge was situated 3.7 km downstream of Portinscale and 0.8 km upstream of the Bassenthwaite Lake inflow. It was installed to record the total suspended sediment input to Bassenthwaite Lake from the River Derwent, and (in comparison with the Portinscale site) to monitor changes in suspended sediment storage and transfers in the lowland area of the River Derwent (Figure 3.1). To monitor suspended sediment transfers from Newlands Beck, the second major tributary at the southern end of Bassenthwaite Lake, a station was installed at Newlands Bridge, 3.4 km upstream of the Lake. The fourth station was installed 0.2 km downstream of the Bassenthwaite Lake outflow near Ouse Bridge, with the aim to monitor suspended sediment transfer outputs from the Lake. The monitoring equipment at each site comprised an automatic water sampler and a datalogger (Figure 3.4), to which a turbidity probe was connected.

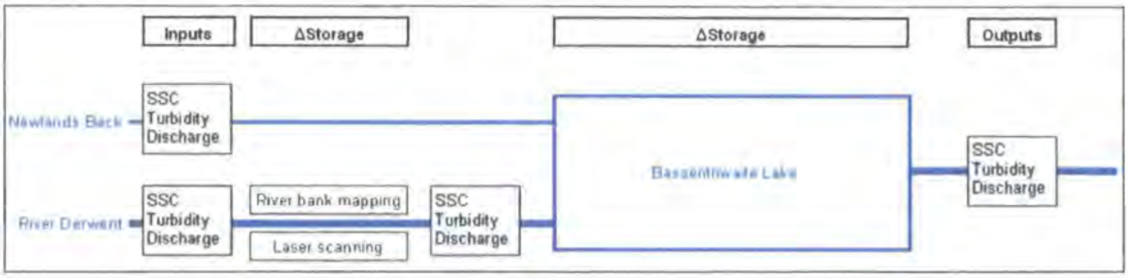

Figure 3.1: The monitoring framework and fieldwork tasks undertaken during fieldwork for this research project, showing their place in the sediment budget of the Bassenthwaite catchment.

Two of the stations (Portinscale and Newlands Bridge) had been operating since November 2004 and had collected 22 months of data prior to the start of this project. The stations at Ouse Bridge and Low Stock Bridge were established in January and December 2005, respectively, and therefore have shorter data records. However, the record of turbidity measurements is not fully continuous due to a period of maintenance following flooding in December 2007, which caused damage to the dataloggers and water samplers at Ouse Bridge and Low Stock Bridge, and the turbidity probes and cabling at Newlands Bridge and Portinscale. Furthermore, drift in background turbidity values has occurred when the wiper cleaning mechanism on turbidity probes has not functioned, leading to unreliable values being recorded during some short periods. The turbidity record at Ouse Bridge is incomplete due to extensive repairs and repositioning of the station (as a result of the damage detailed above) and extensive drift, and therefore it is not used in the analysis of suspended sediment transfers (Section

4.1). These are relatively minor limitations and a sufficient number of values have been recorded to establish long-term trends, suspended sediment loads, and turbidity variations during large events.

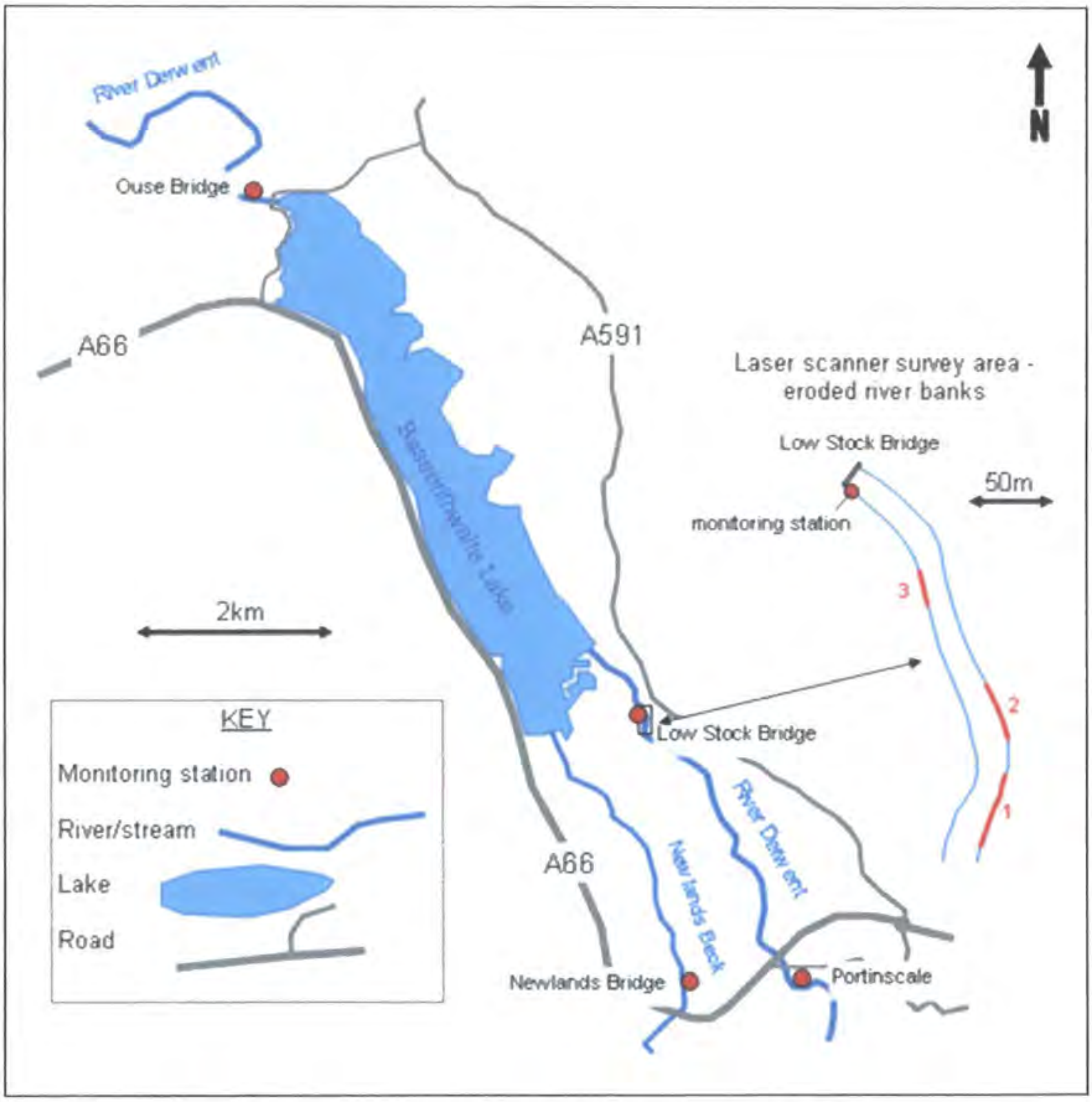

Figure 3.2: Map of the Bassenthwaite Lake area, showing the four monitoring stations used for data collection in this project, in addition to the river bank erosion study area near Low Stock Bridge.

Figure 3.3: Monitoring stations used to collect turbidity data and river water samples:
Top row: left - Portinscale (River Derwent inflow, NY 251 239), right - Low Stock Bridge (River Derwent inflow, NY 236 268).
Bottom row: left - Newlands Bridge (Newlands Beck inflow, NY 240 239), right – Ouse Bridge (River Derwent outflow, NY 199 321).

Figure 3.4: Field monitoring station at Ouse Bridge. The elevated cage (1) contains the automatic water sampler and datalogger (not visible). The black pipe (2) leading down the bank contains the turbidity probe wire, water sampler tube, sampler float switch and pressure transducer. The turbidity probe and water sampler tube are attached to the bank face at the stilling well (3). The two solar panels on the cage supply power to the datalogger battery. The hut close to the cage is an Environment Agency river level and flow gauging site, which collects river stage and discharge data.

3.2 Monitoring suspended sediment transfers: river water samples and turbidity data collection

Suspended sediment concentration data has been collected throughout the research period of this project, to add to the database of concentrations established prior to October 2006. These samples have been taken by river water samplers at each monitoring station and additional samples have been collected at the monitoring stations by hand or using the sampler during field visits. The automatic water samplers can be programmed to sample at either regular time intervals or at a particular river level, as a float switch is attached to the sampler. This latter feature has proved useful in recording suspended sediment concentrations at high river flows during storms. The main purpose of additional hand/grab samples was to obtain further useful samples (e.g. at higher river flows), as well as for calibration purposes. Over the monitoring period, an attempt has been made to sample a larger proportion of high flow events and high suspended sediment concentrations, by using flow-dependent sampling at the automatic water samplers and collecting grab samples during high flow events. The reason for this is because high-magnitude, low-frequency pulses of sediment play a major role in sedimentation and are therefore important to quantify. In total, 463 river water samples were collected at the four monitoring stations during the period November 2004 – May 2007, of which 154 samples were collected during the field monitoring period of this research project (October 2006 – May 2007).

The samples were then filtered and weighed to calculate the suspended sediment concentration of each sample. To work out the suspended sediment concentration of a water sample, a Buchner filtration system was used. The sample is drained through a pre-weighed, desiccated filter paper (retention time = 43 μm), before being placed in an oven at 105 °C for 24 hours. The filter paper is then placed into a desiccator for ca. 15 minutes to remove moisture, and then weighed. The difference between this weight and the pre-filtration weight equals the sediment weight, which can then be divided by the volume of water in the sample to calculate the suspended sediment concentration of the sample (mg l^{-1}).

A database of suspended sediment concentrations has therefore been compiled for the four monitoring stations.

Logistically, it was not possible to continuously sample river water at short time intervals. Therefore, indirect estimation of suspended sediment concentrations were made using turbidity measurements, which were measured using turbidity probes at the four monitoring stations. Turbidity is defined as "an expression of the optical property of a medium which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample" (Lawler 2005, Lawler et al. 2006). This scattering takes place due to the presence of particulates in the water, which include suspended sediment particles. The unit of turbidity measurements is the Nepholometric Turbidity Unit (NTU). The association of high turbidity values with high suspended sediment concentrations enables turbidity values to be used for estimating suspended sediment loads during periods when river water is not directly sampled. To calculate suspended sediment loads from turbidity values, an approximate conversion (1.1 NTU = 1 mg l^{-1}) was used, based upon observations in suspended sediment monitoring in other studies. Relative values are unaffected by this conversion as all four turbidity meters were calibrated to the same NTU standards. River discharge data is also collected by the Environment Agency from its gauging stations at Portinscale, Newlands Bridge and Ouse Bridge. As river discharge is an important determinant upon suspended sediment transfers (e.g. Walling and Webb 1981), it is important to compare the river discharge records during the main period of continuous turbidity monitoring that was used to calculate suspended sediment loads (April-November 2006) with the longer-term flow records from the gauging stations on the River Derwent and Newlands Beck. Comparative flow duration curves for Ouse Bridge, Portinscale and Newlands Bridge monitoring stations are shown below (Figure 3.5). At Ouse Bridge, both high and low flows are over-represented in the period of turbidity monitoring, while at Portinscale although the flow duration curves are approximately parallel, high flows in particular appear more over-represented (Figure 3.5). By contrast, the Newlands Bridge flow duration curves are similar for discharges exceeded less than 30% of the time, but moderate-lower flows appear to be represented less over the turbidity monitoring period than in the full record. Overall, events exceeded more than 20% of the time are more prevalent at Portinscale and Ouse Bridge in particular. This would tend to increase the relative importance of suspended sediment delivery on the River Derwent during this period. However, it is notable that the full discharge records of Portinscale and Ouse Bridge began in 1976, in comparison with the Newlands Bridge record which was established in 2004, so this comparison is not a balanced one.

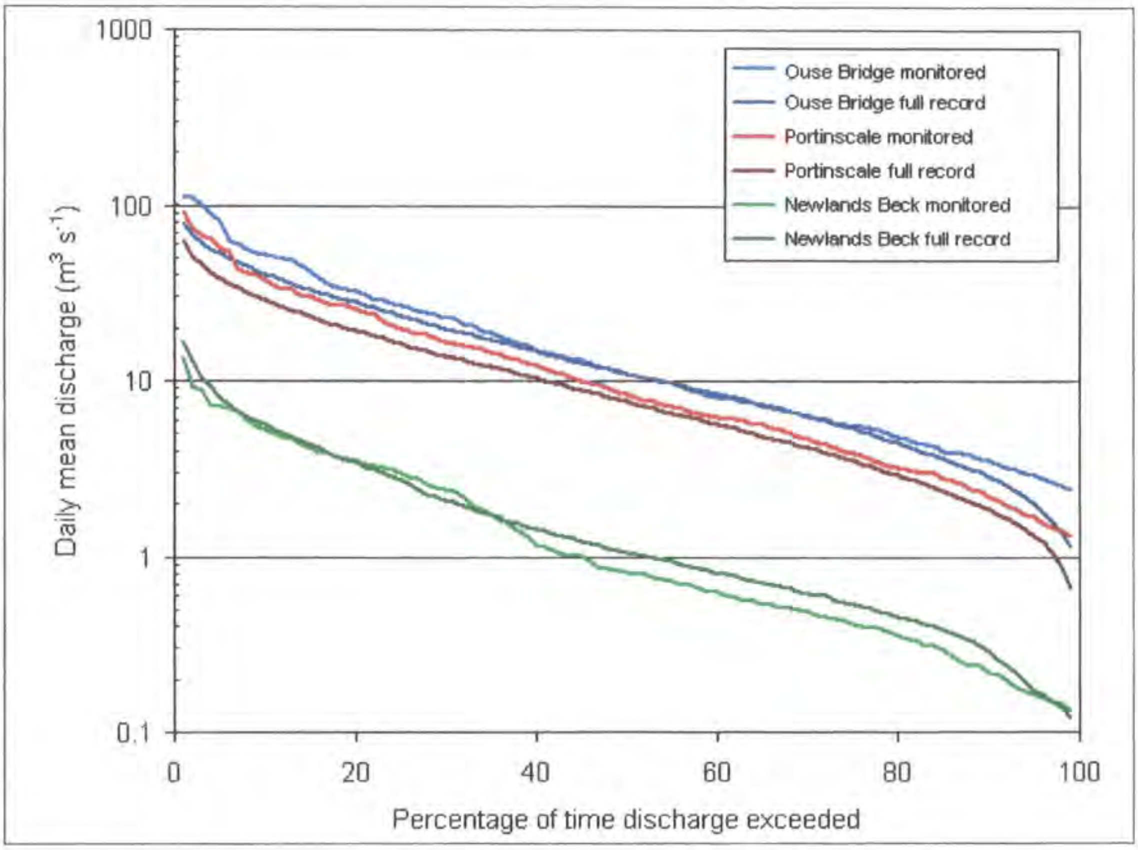

Figure 3.5: Flow duration curves for the gauging stations at Ouse Bridge, Portinscale and Newlands Beck, for both the main turbidity monitoring period (April-November 2006) and the full discharge record at the stations (Ouse Bridge and Portinscale 1976-present, Newlands Bridge 2004-present). Discharge data provided by the Environment Agency.

The datalogger at each monitoring station recorded turbidity data at 15 minute intervals. This data was downloaded onto a laptop during field visits. Aside from these data collection tasks, regular routine maintenance of the sites took place throughout the year (replacing batteries and turbidity probe wipers). Following the flooding of November-December 2006, two samplers and two dataloggers (at Ouse Bridge and Low Stock Bridge) were damaged by flooding and turbulent water flows, in addition to the turbidity probe cabling at Newlands

Bridge was snapped by debris accumulation. The sites were repaired during the winter and were in working order by March 2007.

3.3 River bank erosion survey

The presence of widespread river bank erosion on the 5.7km reach of the River Derwent between Derwent Water and Bassenthwaite Lake has been identified by sediment supply risk analyses, field surveys, studies of historical channel change and field observations (Section 2.2). This section of river was therefore selected as the river bank erosion study area for the project.

Following the consideration of river bank erosion mechanisms (Section 2.4.2), the key task during field surveying was to map the extent of overall bank erosion on the River Derwent, and identify areas of the river channel that are either undergoing or at risk of mass bank failures. Therefore, the study into bank erosion on the River Derwent comprised two main areas: a river bank reconnaissance survey of bank erosion on the Derwent between Derwent Water and Bassenthwaite Lake, and a survey of river bank erosion rates and morphological change.

3.3.1 River bank erosion extent survey: bank reconnaissance and mapping

To assess the extent of river bank erosion on the River Derwent, it was important to produce an accurate reconnaissance survey and mapping of river bank erosion features, especially on the 5.7km lowland reach between Derwent Water and Bassenthwaite Lake which has been identified by Orr et al. (2004) as having a large area of eroding river banks. Therefore, a survey of eroded river bank features was undertaken using a differential GPS unit (model: Leica GPS 1200) in May-July 2007. GPS point data of erosion features was collected using a mobile rover unit and transferred to ArcMap, producing an overall map of river bank erosion extent. Field mapping was used in areas where overhanging tree cover prevented the use of the GPS. In addition, photographs were taken in order to add detail to the riverbank mapping.

Various features of river bank were identified and mapped using a set of identifying criteria (Table 3.1). The mapping feature code was determined by important features of bank erosion suggested by the review of river bank erosion mechanisms and processes (Section 2.4), and was designed to assess the extent of river bank erosion by identifying large areas of the bank that were eroding (eroded river banks and poaching scars) whilst also identifying additional features (failed blocks, talus slopes) that indicate active river bank erosion and sediment supply. In addition, areas of river bank management (e.g. revetments, gabions) were also mapped, as they represent attempts to prevent riverbank erosion. Furthermore, structures present which may influence river bank stability (e.g. bridges, walls) were included in the river bank mapping.

Mapping feature	Identifying criteria
Eroded river bank	Large area of bank erosion, entire bank height and majority of bank face composed of exposed soil.
Poaching scar	Large area of bank erosion caused by grazing animals. Exposed soil and evidence of trampling, often diversion of fencing at larger scars.
Failed block	Block of material collapsed from river bank. Distinction between vegetated and non-vegetated blocks.
Crack	Tension crack sub-parallel to the bank line, suggesting potential block failure.
Talus slope	Slope of coarse material at foot of river bank, formed by erosion of the bank.
Revetments	Man-made river bank defences. Typically of stone or wooden construction.

Table 3.1: The definitions used to map river bank erosion.

The mapping definitions used during the mapping survey (Table 3.1) were designed to identify the extent of river bank erosion, as well as to map the location of features which show direct inputs of sediment to the river channel. Sections of river bank erosion included exposed river bank faces and poaching scars in agricultural areas. Failed blocks of material are important as they are clear evidence of the active delivery of material from the river bank and are indicative of large bank failures, especially cantilever failures (Section 2.4.2.1) In addition, areas of bank reinforcement (e.g. stone revetments) were also surveyed, as they represent attempts to manage erosion.

At eroded river bank sections, measurements were taken of the river bank profile. In all, 77 bank profiles were recorded. Measurements were taken at eroded reaches, at locations representative of the eroded river bank as a whole. These are extremely important in assessing the areas of river bank which are susceptible to large bank failures, as bank geometry (river bank height, gradient, and the amount of undercutting) plays an important role in affecting bank stability (Section 2.4.1) and therefore the susceptibility of the bank to further erosion and sediment addition to the river channel. The measurements taken are shown in Figure 3.6. Additionally, the bank structure at such profiles was noted, as the composition of a river bank can play a major role in determining overall bank stability and failure mechanisms (Sections 2.4.1, 2.4.2).

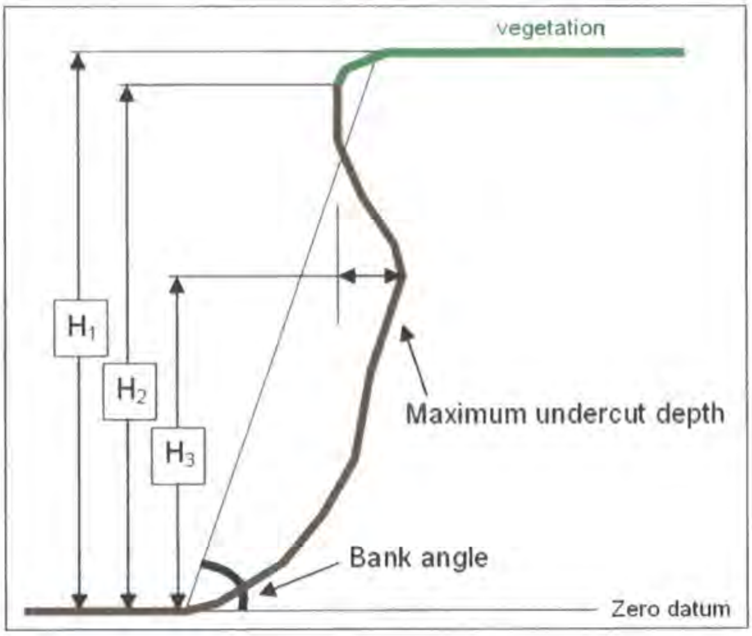

Figure 3.6: Bank profile measurements collected during mapping. H_1 = maximum bank height, H_2 = height of eroded part of bank, H_3 = height of bank to maximum undercut depth.

3.3.2 River bank morphological change survey: laser scanning

It is very difficult to quantify the total volume of material eroded from river banks along an entire river length, which (on the Derwent) would require several surveys of over 11 km of river banks. Therefore, this project decided to study in detail the rate of erosion and morphological change on three river banks between Low and High Stock Bridges (Figure 3.7, Table 3.2). Over a four month period between 13th March 2007 and 15th June 2007, three bank reaches (Figures 3.2, 3.7) were surveyed twice using a terrestrial laser scanner (Trimble GS200). The scanner was used to produce virtual profiles of the river bank surface in the form of a point cloud. When the banks were re-surveyed, it was possible to compare scans and identify areas of material removal and bank morphological change.

The study of river bank erosion using the laser scanner was carried out as a pilot study. The study period (3 months) proved too short to document any large bank changes, particularly as no scans were taken during winter when a large volume of material is typically eroded from river banks (Section 2.4.5). However, the aim of this study was to asses the usefulness of the laser scanning technique for the study of river bank erosion. The key advantages of the use of a laser scanner are the ability to calculate volumes of sediment removed from the river bank, as well as visualise landforms of bank erosion and assess failure mechanisms. The scanner is potentially a considerable improvement over previous fieldwork methods for analysing river bank erosion, which were typically in the form of field observations (e.g. Wolman 1967) and estimations of bank retreat rate at erosion pins (e.g. Lawler et al. 1997).

The use of laser surveying to measure soil erosion was developed in the early 1990s, with some relatively basic techniques using video camera recordings of laser positions (Konstant 1991). Later, laser scanners were used to create instantaneous profiles of soil microtopography (Darboux and Huang 2004), and further techniques using airborne laser scanning to create digital terrain models of stream bank form (Witte et al. 2001) and bank erosion (Thoma et al. 2005). The use of laser scanning to create virtual models of river bank faces has been a relatively recent development, however aerial laser scanning of eroded banks in Minnesota (Thoma et al. 2001, 2002) and Virginia (Pizzuto et al. 2007) have taken place. Therefore, the use of a terrestrial, ground-based laser scanner to monitor river bank erosion is a comparatively new technique.

Figure 3.7: The three river bank sections analysed in the river bank erosion study in this project, showing bank 1 (top), bank 2 (middle) and bank 3 (bottom).

Bank number	Derwent channel bank	Length (m)	Maximum height (m)	Mean angle (°)	Maximum undercut (mm)
1	East bank	53	1.95	54	340
2	East bank	24	1.54	42	0
3	West bank	14	1.8	80	270

Table 3.2: Summary of the morphological characteristics of the eroded bank sections monitored in this project.

The three river banks (Figure 3.7) comprising the bank erosion rate study area were selected as they are generally representative of the River Derwent's bank types in terms of composition, land use and vegetation. Dominant bank materials are fine, cohesive overbank deposits with some sections of coarser gravels. Bank 1 is a dominantly cohesive river bank, while bank 2 is partly composite with a clear layer of gravel overlain by cohesive material at the upstream end of the section. Bank 3 meanwhile is a composite bank with non-cohesive coarse material dominating the bank face. All the banks are in excess of 1.5 m in height (Table 3.2). River banks 1 and 2 are located on the outside of a meander bend, a planform characteristic generally associated with high erosion rates (e.g. Hooke 1979, 1980). River bank 3 is situated on an approximately straight river reach.

The dominant land use in the bank erosion study area, grazing, is also representative of the reach as a whole. The western river bank is protected from poaching by a fence, therefore the river channel on this bank cannot be accessed by animals, except at a restricted point upstream of bank 3. The eastern bank is not protected and animals (sheep and cattle) can graze up to the bank face. The dominant vegetation type on the areas adjacent to the river bank is grass (longer on the western bank), although the western bank has been planted with young trees on the bank top. There are some small trees and bushes on the east bank, although none at the two bank erosion sites. The downstream river reaches close to Low Stock Bridge are fenced off from the grazing land, and there is an area of large, mature trees and bushes on the east bank, and there is also a small area of trees in the field above the west bank at the Low Stock Bridge monitoring station.

Before the erosion study began, reference points for scan comparisons were installed at the erosion sites. Threaded rods (c. 1 m length, 20 mm diameter) were inserted into the river bank faces, onto which reference targets (200 mm x 200 mm) were mounted during scanning (Figure 3.8). Twelve reference points are used at the sites, with five used at the longest bank reach (bank 1), four used at bank 2 and three used at bank 3. The scanner was set at a resolution of 30 mm at a distance of approximately 20 m from the surface being scanned.

The base scans for the bank erosion study were carried out on the 13th March 2007 (Figure 3.8). To carry out a bank scan, the scanner was set up on the opposite river bank, which enables the clearest view of the surface to be scanned (Figures 3.8). The laser scanner firstly scans the reference points at each bank section, before carrying out a detailed scan of the whole section. One scan was carried out at banks 2 and 3; however, the greater length of bank 1 necessitated two scans, hence four benchmarks were established at the survey sites. Following the base scans, a second laser scan took place on the 15th June 2007.

Figure 3.8: The laser scanner taking the first base scan of river bank 1, 13th March 2007. The laser scanner is mounted on the yellow tripod. The scan targets used for referencing the scans are indicated (circled).

Once all data was collected, processing of the point cloud data was undertaken using RealWorks software. Following georeferencing, the point clouds could be overlain where necessary (at bank 1, where two separate scans of the bank were taken due to the bank's length). Once the two scans from the two dates were overlain, areas of erosion or morphological difference between the scans could be identified. Errors in scan matching were less than 0.001 m.

3.4 Summary

The methods and techniques described here aimed to collect accurate data relevant to the aims and research questions of the project (Section 1.6). A key theme is the sediment budget concept, as suspended sediment inputs to Bassenthwaite Lake and sediment storage play a large role in the ecological problems in the lake basin, and therefore analysing the potential sources of fine sediment and the characteristics of suspended sediment transfers to Bassenthwaite Lake are very important. The Bassenthwaite sediment budget is assessed through both the suspended sediment transfer monitoring and the river bank erosion study. The suspended sediment monitoring therefore aimed to quantify the suspended sediment transfers to Bassenthwaite Lake, as well as the overall lowland catchment sediment budget including suspended sediment storage in Bassenthwaite Lake; with the bank erosion survey aiming to assess the potential for river bank erosion to contribute to such sediment inputs.

The data collected was used in three ways: Firstly, an analysis of the suspended sediment concentration data was undertaken in order to assess trends in suspended sediment transfers, as well as to identify the most important parts of the catchment sediment budget, including the nature of suspended sediment inputs and the relative importance of the River Derwent and Newlands Beck for sediment transfers. Secondly, the river bank mapping and reconnaissance information was used to calculate the extent of river bank erosion on the lowland River Derwent and analyse risks of sediment delivery in such areas. Thirdly, the laser scanning data from the banks of the River Derwent was used to assess the processes of river bank erosion operating on a reach of the Derwent.

CHAPTER FOUR

RESULTS

This chapter comprises data analysis, results and discussion in order to answer the two research questions in this project (Section 1.6). The chapter is comprised of two main sections, which correspond to the initial research questions:

- Section 4.1: The characteristics of suspended sediment transfers to Bassenthwaite Lake.
- Section 4.2: Assessment of river bank erosion on the lowland River Derwent between Derwent Water and Bassenthwaite Lake.

4.1 The characteristics of suspended sediment transfers to Bassenthwaite Lake

This section presents results of suspended sediment concentrations (SSC) from the river water samples and turbidity monitoring data collected during the course of this project (Sections 3.1, 3.2). The literature review suggests the presence of several potential sources of sediment in the catchment (Sections 2.1, 2.2). Furthermore, there is a lack of knowledge of the overall sediment load being transported to Bassenthwaite Lake and uncertainty as to the relative importance of different tributaries to sediment delivery to the lake (Section 2.1). The data collection and structure of the analysis is described below (Section 4.1.1).

4.1.1 Suspended sediment monitoring data collection

As described in the methodology, suspended sediment monitoring in the Bassenthwaite Lake lowland catchment took place between November 2004 and May 2007 at four monitoring stations located on the lowland rivers near Bassenthwaite Lake (Section 3.1). The monitoring itself has involved the collection of two sets of data: direct measurements of the concentration of sediment being transported in river water samples, and measurements of turbidity, which gives an indication of the particulate content of river water (Section 3.2). Both methodologies have been used to assess characteristics of sediment transfers in the Bassenthwaite lowland catchment, in particular the nature of material delivery to the lake, which is crucial to the ecological problems faced there (Section 1.3).

In total, 463 river water samples have been collected during the overall suspended sediment monitoring period (November 2004 – May 2007). An analysis of the suspended sediment concentrations of these samples is detailed below (Section 4.2). Sampling was biased towards higher suspended sediment concentrations in order to quantify sediment pulses, which has elevated average concentrations above background values; however, differences in concentrations between the monitoring stations are valid. Some sites were established earlier than others, and so there are differences in the number of samples collected. For example, the Portinscale station was established in November 2004 and 2005 samples have been collected, while the Low Stock Bridge station was set up in

December 2005 and only 67 samples have been taken at that station. On the 2nd September 2006, 24 river water samples were taken from all four monitoring stations during a high flow event, enabling an analysis of sediment transfer characteristics to be made over a shorter time scale.

The turbidity record analysed below complements the suspended sediment data as it enables a more continuous and complete record of sediment transfer monitoring, as the 15-minute sampling enables data collection during periods of time between water sampling. The values have been converted to suspended sediment concentration values (in mg l^{-1}) using the conversion of 1.1 NTU = 1 mg l^{-1}, which has been shown to be a good approximate conversion between the two measures of fine sediment transport, based upon monitoring in other studies. There have been periods of disruption to the record due to some equipment damage, particularly during the flooding of December 2006 – January 2007, and turbidity drift, with the most incomplete record being at Ouse Bridge. However, there is a continuous record of turbidity values at 15-minute intervals at the three inflow monitoring stations between 1st April and 30th November 2006. This is the most complete record of turbidity values during monitoring and is the one which is used in the analysis below.

The river water sample and turbidity records described above are integrated in the analysis of suspended sediment transfers in the Bassenthwaite Lake lowland catchment (Table 4.1). The longer river water sample record is used to analyse overall characteristics of suspended sediment transfers in the lowland Bassenthwaite Lake catchment (Section 4.1.2), and spatial variations in suspended sediment transfers between the four monitoring stations (Section 4.1.3.1). The continuous monitoring of turbidity between April and November 2006 is used to calculate the suspended sediment transfers to Bassenthwaite Lake, including the overall sediment loads being transported on the River Derwent and Newlands Beck (Section 4.1.3.2), the characteristics of suspended sediment transfers on the River Derwent (Section 4.1.3.3) and hysteresis analysis of relationships between flow discharge and suspended sediment concentration variations during high discharge events (Section 4.1.3.4). A summary of the conclusions of this analysis are included in Section 4.1.4.

Section	Water samples (November 2004-May 2007)	Turbidity data (April-November 2006)
4.1.2 Overall characteristics of suspended sediment transfers in the lowland Bassenthwaite Lake catchment	√	
4.1.3.1 Spatial variations in suspended sediment transfers, 2004-7	√	
4.1.3.2 Suspended sediment load estimates, April-November 2006		√
4.1.3.3 Suspended sediment transfer characteristics on the River Derwent		√
4.1.3.4 Hysteresis analysis and suspended sediment transfers during discharge events		√

Table 4.1: The structure of the data analysis, showing the integration of the water sample and turbidity data records into the analysis.

4.1.2 Overall characteristics of suspended sediment transfers in the lowland Bassenthwaite Lake catchment

During the monitoring period (November 2004 to May 2007), suspended sediment transport on the River Derwent and Newlands Beck has been highly episodic. 65% of all water samples had suspended sediment concentrations below 10 mg l^{-1}, with just below 44% of samples containing less than 5 mg l^{-1} (Figure 4.1, Table 4.2). In contrast, a very small proportion of samples (5.4%) featured concentrations in excess of 50 mg l^{-1}. The dominance of low suspended sediment conditions in the catchment is further shown by the disparity between the overall mean (13.4 mg l^{-1}) and median (6.3 mg l^{-1}) concentrations in the catchment, which suggests the presence of a large frequency of low suspended sediment concentrations and a small number of much higher concentrations. This is supported by the fact that less than a third (28%) of all samples are above the catchment mean.

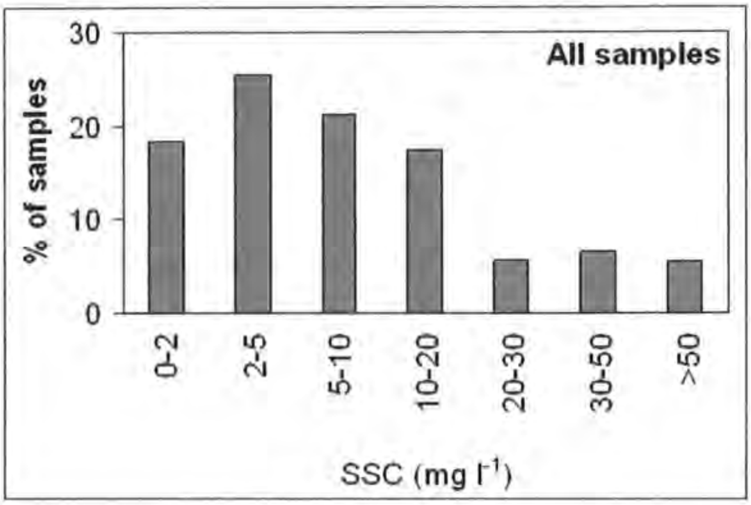

Figure 4.1: The distribution of suspended sediment concentrations recorded at the four monitoring stations during the whole monitoring period (2004-7).

Overall water sample record	
Number of water samples	463
Mean SSC (mg l^{-1})	13.4
Median SSC	6.3
Standard deviation	20.3
% of samples below mean	72%
% of samples above mean	28%

Table 4.2: Average suspended sediment concentrations recorded at all monitoring stations (2004-7).

4.1.3 Spatial variations in suspended sediment transfers in the lowland Bassenthwaite Lake catchment

The following section is an analysis of suspended sediment concentration (SSC) characteristics of both the river water sample and turbidity data records, over the 2004-7 and April-November 2006 monitoring periods respectively.

4.1.3.1 Spatial variations in suspended sediment concentrations, 2004-7

Over the entire monitoring period, the River Derwent is seen to dominate the suspended sediment input to Bassenthwaite Lake (Table 4.3). The mean suspended sediment concentration recorded at Newlands Bridge on Newlands Beck (9.6 mg l^{-1}), was nearly 56% lower than that of Low Stock Bridge on the Derwent (21.7 mg l^{-1}), with a similar 58% disparity in median concentrations. Peak sediment fluxes on the River Derwent were also much greater than those on Newlands Beck; the maximum sediment peak recorded on the Derwent (184.45 mg l^{-1} at Portinscale) is nearly three times the peak concentration at Newlands Bridge (64.25 mg l^{-1}). Twelve concentrations recorded on the Derwent are higher than the Newlands Bridge maximum, and of all flows above 50 mg l^{-1}, only 3 were recorded at Newlands Bridge (compared with 12 on the two River Derwent stations). Furthermore, 71% of all samples at Newlands Beck contained low (<10 mg l^{-1}) suspended sediment concentrations, compared with 52% of samples at Low Stock Bridge, the dominance of low suspended sediment concentrations there is also indicated by the low median concentration (3.9 mg l^{-1}) (Figure 4.2).

There is also a considerable difference in suspended sediment concentrations between the two River Derwent monitoring stations. The mean concentration at Low Stock Bridge is over 8 mg l^{-1} higher than the Portinscale mean (Table 4.3). This reflects a greater proportion of higher concentrations recorded at Low Stock Bridge, especially the highest concentrations in excess of 50 mg l^{-1}, which were observed in c. 15% of water samples from Low Stock Bridge but only 4% of Portinscale samples (Figure 4.2). Between the two sites, Portinscale also has a greater number of low concentration samples, particularly in the 2-5 mg l^{-1} range. The greater variation in concentrations at Low Stock Bridge is also reflected in the much larger standard deviation at the site (30.5 compared with 18.8 at Portinscale) (Table 4.3).

The suspended sediment record at Newlands Bridge is one of predominantly low concentrations, with few high concentrations and low variability of values. The mean SSC (9.6 mg l^{-1}), median SSC (3.9 mg l^{-1}) and maximum recorded concentration (64.25 mg l^{-1}) at Newlands Bridge are the lowest recorded at all the monitoring stations. It is significant that well over a third (37%) of all samples taken at the station contained very low concentrations (below 2 mg l^{-1}), a proportion much greater than at the other monitoring stations (average proportion in this range = 9-11%).

At Ouse Bridge, low suspended sediment concentrations dominate the record, with over 80% of all recorded concentrations containing below 10 mg l^{-1} of sediment (Figure 4.2), and a median concentration of just over 4 mg l^{-1} (Table 4.3). Despite this, the mean value and standard deviation at the site are elevated by a set of four very high values in excess of 80 mg l^{-1} recorded on the 11th November 2006 which shows a significant sediment pulse from Bassenthwaite Lake. If the sum of the Newlands Bridge and Low Stock Bridge mean concentrations may be regarded as the average sediment input to the lake, then the Ouse Bridge mean concentration (12.19 mg l^{-1}) is only 39% of the total input. The implication of this calculation is that suspended sediment inputs to Bassenthwaite Lake are greater in volume than suspended sediment outputs from the lake, and therefore it appears that there is considerable storage of sediment in the lake basin, which supports the findings of several studies of sedimentation characteristics within the lake (Section 1.4).

	Portinscale	Low Stock Bridge	Newlands Bridge	Ouse Bridge
Number of samples	205	67	139	52
Mean SSC (mg l^{-1})	13.6	21.7	9.6	12.2
Median SSC	7.3	9.3	3.9	4.1
Maximum SSC	184.45	163.77	64.25	91.65
Minimum SSC	0.26	0.43	0.11	0.60
Standard deviation	18.8	30.5	12.8	23.5

Table 4.3: Suspended sediment concentration (SSC) characteristics from water samples taken at the four monitoring stations between November 2004 and May 2007.

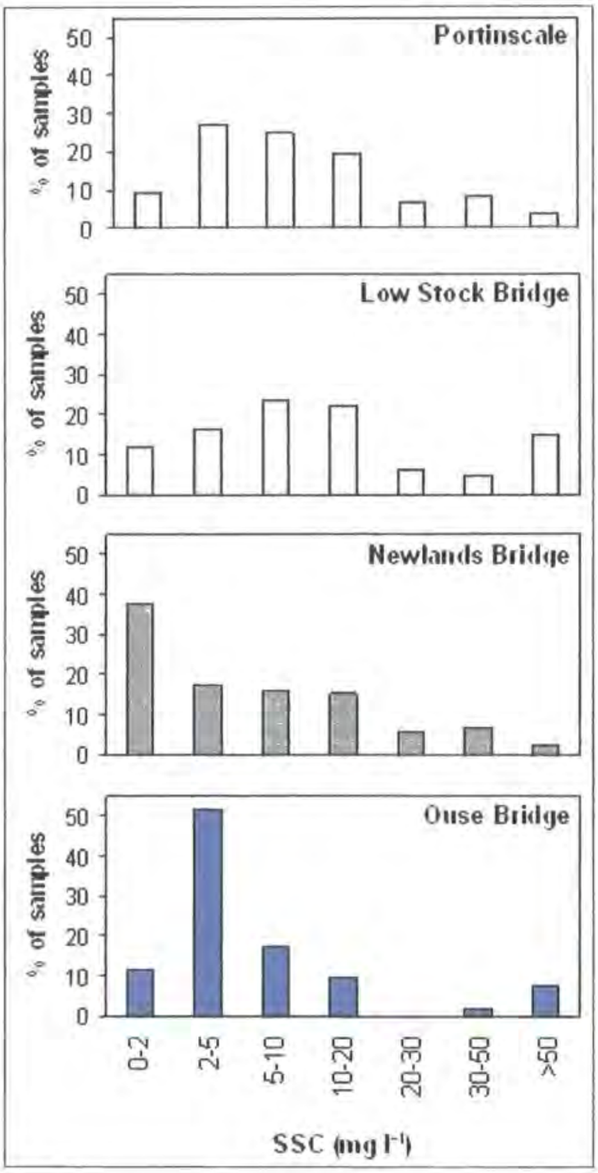

Figure 4.2: Histogram showing the distribution of suspended sediment concentrations at the four monitoring stations.

The suspended sediment concentrations described above could be biased if the proportion of water samples collected at higher flows was greater at some monitoring stations than others. However, the mean discharges recorded at the time of water sample collection are similar at Portinscale, Low Stock Bridge and Ouse Bridge (Table 4.4), although the standard deviations of the three stations are slightly different, suggesting a greater range of flows was sampled at Ouse Bridge than at the two inflow stations. It is notable that the Newlands Bridge mean discharge at time of sample collection is considerably lower than the River Derwent stations; this reflects the smaller catchment area and naturally lower discharge at Newlands Beck reflected in the literature (Beattie et al. 1996, Hall et al. 2001).

Monitoring station	Mean discharge ($m^3 s^{-1}$)	Standard deviation
Portinscale	25.6	14.4
Low Stock Bridge	27.7	16.0
Newlands Bridge	6.2	3.4
Ouse Bridge	27.5	19.1

Table 4.4: Mean discharges at times of water sample collection at the four monitoring stations.

On the afternoon of the 2nd September 2006, the four automatic water samplers each collected 24 samples on a flow-dependent basis during a high flow event. Discharge records from Portinscale gauging station suggest that discharges were high for much of the day, with a peak discharge of 31.5 $m^3 s^{-1}$ at 19:30. The Newlands Bridge discharge record suggests an earlier peak of 14.7 $m^3 s^{-1}$ at 16:00. Samples were taken from all stations at 15 minute intervals. The sampler at Newlands Bridge collected its samples between 12:00 and 17:45, while the three other samplers operated between 18:00 and 23:45. These samples provide a record of the high suspended sediment concentrations at the three inflow monitoring stations, several large suspended sediment peaks at Low Stock Bridge, and an unusual response of suspended sediment concentrations at Ouse Bridge (Table 4.5, Figure 4.3). The mean concentrations recorded on the

2nd September at Portinscale, Low Stock Bridge and Newlands Bridge were greater than double the stations' mean concentrations over the long term monitoring period, suggesting a large pulse of sediment flowing into the lake (Table 4.5). However, the responses of the two River Derwent inflow stations were considerably different (Figure 4.3). The suspended sediment concentrations at Portinscale were moderately high across the 6 hour period, with the highest value of 53.77 mg l^{-1} recorded at 18:00, after which concentrations steadily declined to below 20 mg l^{-1} from 21:30 onwards. However, the Low Stock Bridge record is markedly different showing a complex and multi-peaked response. Until 21:00, suspended sediment concentrations were generally low apart from two pulses, during which very high and extreme concentrations (96.16 mg l^{-1} and 163.77 mg l^{-1} are recorded. The difference in maximum concentrations recorded on the day is remarkable, as the Low Stock Bridge peak value of 163.77 mg l^{-1} is over three times the maximum recorded at Portinscale. Unlike the response at Portinscale, there is no general decline in concentrations in the latter half of the monitoring period at Low Stock Bridge, and further sediment pulses were recorded in excess of 80 mg l^{-1} at 23:00 and 23:45. It is also apparent that a greater volume of sediment was recorded at Low Stock Bridge than Portinscale over this period, given that the mean concentration at Low Stock Bridge is 17.06 mg l^{-1} higher than that of Portinscale. In addition, the strong variability in concentrations is reflected in the standard deviation of concentrations being nearly three times higher at Low Stock Bridge than at Portinscale.

During its earlier sampling period, Newlands Beck recorded a lower mean concentration than at Portinscale and especially Low Stock Bridge (Table 4.5), and therefore acted in accordance with the longer-term trend at the sites. Throughout the day, concentrations were moderately high, with a peak of 38.73 mg l^{-1} and 4 other values above 30 mg l^{-1} although such concentrations are well below the maximum and average values recorded at Low Stock Bridge. Three concentrations below 10 mg l^{-1} were recorded, but otherwise the record is one of fluctuating, moderately high sediment concentrations. Converted turbidity values suggest that suspended sediment concentrations steadily declined to low values during the final 6 hours of the day.

The suspended sediment concentration characteristics recorded at Ouse Bridge are drastically different to the other three stations, with Ouse Bridge the only monitoring station to have a lower mean concentration on the 2nd September 2006 than the station's long term average (4.68 mg l^{-1} compared with 12.19 mg l^{-1}) (Table 4.5). All but two suspended sediment concentrations were below 10 mg l^{-1}, with very low variability in concentrations (standard deviation = 3.23 mg l^{-1}). The implication of these figures is that the flux of suspended sediment recorded at the inflow stations did not reach, or was not recorded, at Ouse Bridge. The Ouse Bridge mean concentration, 4.68 mg l^{-1}, is only 7% of the average sediment input on the 2nd September. This suggests that a larger volume of suspended sediment was stored in the lake than under normal flow conditions.

	Portinscale	Low Stock Bridge	Newlands Bridge	Ouse Bridge
Mean SSC (mg l^{-1})	28.60	45.66	20.98	4.68
Median SSC	23.96	31.57	19.17	3.47
Maximum SSC	53.77	163.77	38.73	13.89
Standard deviation	13.31	38.62	10.25	3.23

Table 4.5: Suspended sediment concentrations at the four monitoring stations recorded on 2nd September 2006 (at all sites n = 24).

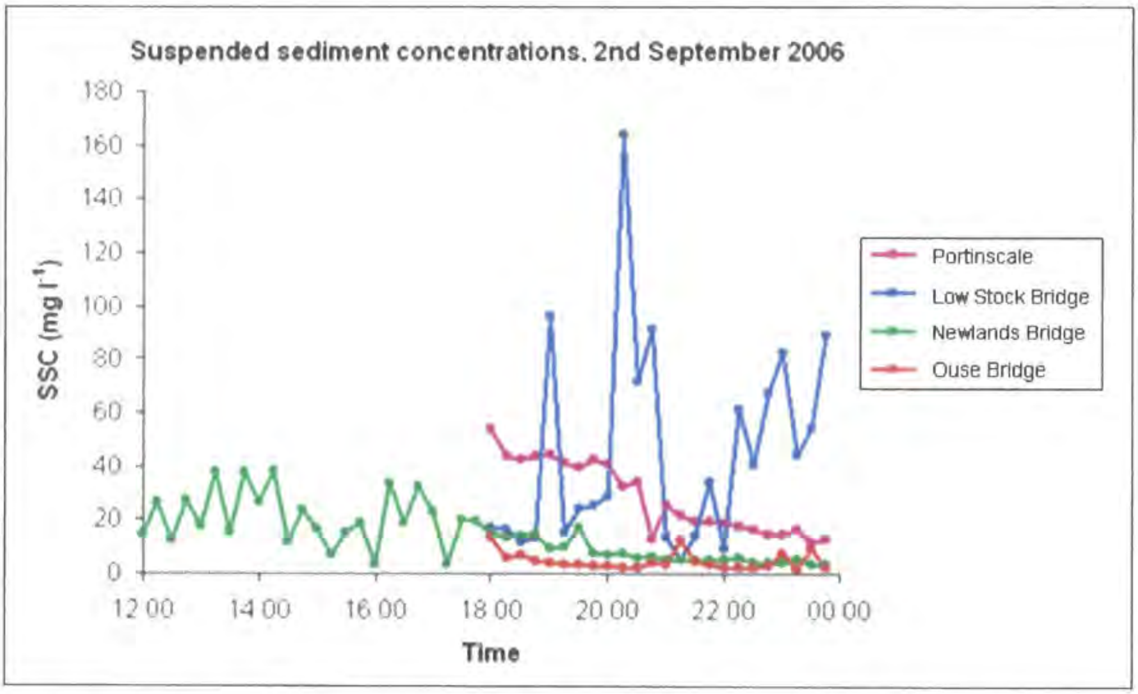

Figure 4.3: Graph showing variations in suspended sediment concentrations recorded at the four monitoring stations during sampling on the 2nd September 2006. Note that the second half of the Newlands Bridge record (18:00-23:45) was retrieved from the turbidity data rather than from water samples.

4.1.3.2 Suspended sediment load estimates, April-November 2006

The continuous turbidity monitoring between April and November 2006 (Section 4.1.1) means that total suspended sediment loads transferred to Bassenthwaite Lake can be quantified for that 8-month period, as well as an estimate of total annual suspended sediment inflows (Table 4.6). The load calculations support the trends indicated by the direct water samples above (Section 4.1.3.1). Over the period, the River Derwent contributed over 80% of fine sediment load to Bassenthwaite Lake, and is again seen to dominate sediment transfer inputs at the south end of Bassenthwaite Lake. Furthermore, there is a notable downstream increase in fine sediment load between the two River Derwent stations of 772 t, which can be extrapolated to an annual 1,158 t increase in suspended sediment load on this reach over a year. The calculations of annual suspended sediment loads (Table 4.6) are estimates as the 8-month turbidity monitoring period did not encompass winter.

These sediment loads support the disparity in mean concentrations between Portinscale and Low Stock Bridge found in the water sample record (Table 4.2), and suggests that sediment addition is taking place on the lowland River Derwent. This trend is supported by the cumulative sediment loads throughout the year (Figure 4.4), which indicate that increases in cumulative sediment load occurred during short periods of time, as evidenced by the stepped profiles of the graphs (Figure 4.4), suggesting the importance of high-magnitude, low-frequency events in sediment transfers described below (Section 4.1.3.3)

Monitoring station	Suspended sediment load (t) (8 months)	Estimated load (t) (Annual)
River Derwent at Portinscale	3,305	4,958
River Derwent at Low Stock Bridge	4,077	6,116
Newlands Beck at Newlands Bridge	807	1,211

Table 4.6: Overall suspended sediment load calculations for the three inflow monitoring stations for a) the 8-month turbidity monitoring period between 1st April and 30th November 2006, b) an estimated annual (12-month) period.

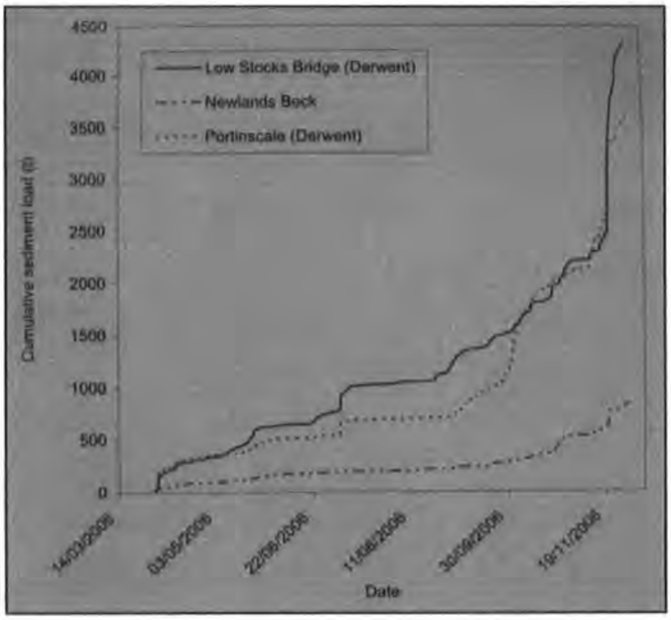

Figure 4.4: Cumulative sediment curves during the 8-month turbidity monitoring period in 2006. Diagram from Warburton (2007).

The above calculations of suspended sediment loads can be compared with the effective catchment areas and stream lengths of the River Derwent and Newlands Beck in order to compare suspended sediment productivity between the subcatchments (Table 4.7). This analysis shows that, even when allowing for the catchment's smaller area and the shorter length of streams within the catchment, the Newlands Beck subcatchment supplies less sediment per km^2 and km of stream than the River Derwent subcatchment. During the extrapolated annual monitoring period, the Derwent catchment (upstream of Low Stock Bridge) produces an estimated 42% more suspended sediment per km^2 than the Newlands Beck catchment upstream of Newlands Bridge, with a comparative 23% difference in productivity per km of stream length (Table 4.7). Furthermore, the reach of the River Derwent between Portinscale and Low Stock Bridge (and its tributaries and their catchment area) produces an estimated 101 t km^2 of suspended sediment over a 12-month period, with a productivity per km of stream length 227% that of the overall effective River Derwent catchment. These observations support the findings of the water sample analysis above (Section 4.1.3.1) and the sediment loads for the River Derwent and Newlands Beck (Table 4.6), as the greater suspended sediment load on the River Derwent results from an overall higher suspended sediment productivity, in addition to a larger catchment area and greater hydraulic input.

Catchment	River Derwent at Portinscale	River Derwent at Low Stock Bridge	River Derwent (Portinscale to Low Stock Bridge)**	Newlands Beck at Newlands Bridge
Effective* catchment area (km^2)	108.83	120.23	11.4	33.9
Effective* stream length (km)	194.58	208.85	14.27	50.68
Suspended sediment load (annual estimate) ($t\ a^{-1}$)	4,958	6,116	1,158	1,211
Suspended sediment yield (area) ($t\ km^2\ a^{-1}$)	45.55	50.87	101.58	35.72
Suspended sediment yield (stream length) ($t\ km\ a^{-1}$)	25.48	29.28	81.15	23.9

*Table 4.7: Suspended sediment productivity related to effective catchment size and stream lengths of the three inflow monitoring stations on the River Derwent and Newlands Beck, as well as the Portinscale-Low Stock Bridge reach of the Derwent. * - the River Derwent's effective catchment area is that downstream of Derwent Water and Thirlmere, on the assumption that these lakes act as suspended sediment sinks. ** - The stream length and catchment area for the River Derwent between Portinscale and Low Stock Bridge includes all streams as well as the main trunk. Catchment area/stream length data from Bassenthwaite GIS Viewer CD (Environment Agency/Forestry Commission 2005).*

4.1.3.3 Suspended sediment transfer characteristics on the River Derwent

The continuous turbidity monitoring between April 1st and November 30th 2006 has been converted to suspended sediment concentration data (Section

4.1.1) which has enabled a record of concentrations at 15-minute intervals to be compiled. This is useful for an analysis of sediment transfers over this period, particularly the quantification of sediment inputs and delivery patterns on the River Derwent. This analysis complements the analysis of the water sample record above (Section 4.1.3.1).

The suspended sediment transfers during April-November 2006 had similar overall characteristics to the river water samples (Section 4.1.3.1) as during the majority of the period, concentrations are low (Figure 4.5). For over three-quarters of the duration of the turbidity monitoring period, suspended sediment concentrations were below 10 mg l^{-1}. Only 11% of all samples were in excess of 20 mg l^{-1}, and very high concentrations (in excess of 50 mg l^{-1}) were only recorded during 3% of measurements. However, such high flows were responsible for transferring a very high proportion of the overall inflow suspended sediment load. The 3% of the period where concentrations were above 50 mg l^{-1} transported 41% of the entire sediment inflow to the lake. The 11% of measurements with concentrations above 20 mg l^{-1} transported nearly two-thirds (64%) of the overall sediment load. The low concentrations (SSC<10 mg l^{-1}) were only responsible for the transport of just over a fifth (21.2%) of total sediment load. Therefore, a large volume of overall suspended sediment transfers on the Derwent and Newlands Beck occurred during low-frequency large sediment pulses. This pattern of suspended sediment transfer is highlighted in the literature (e.g. Thompson and Oldfield 1986, Walling and Webb 1987).

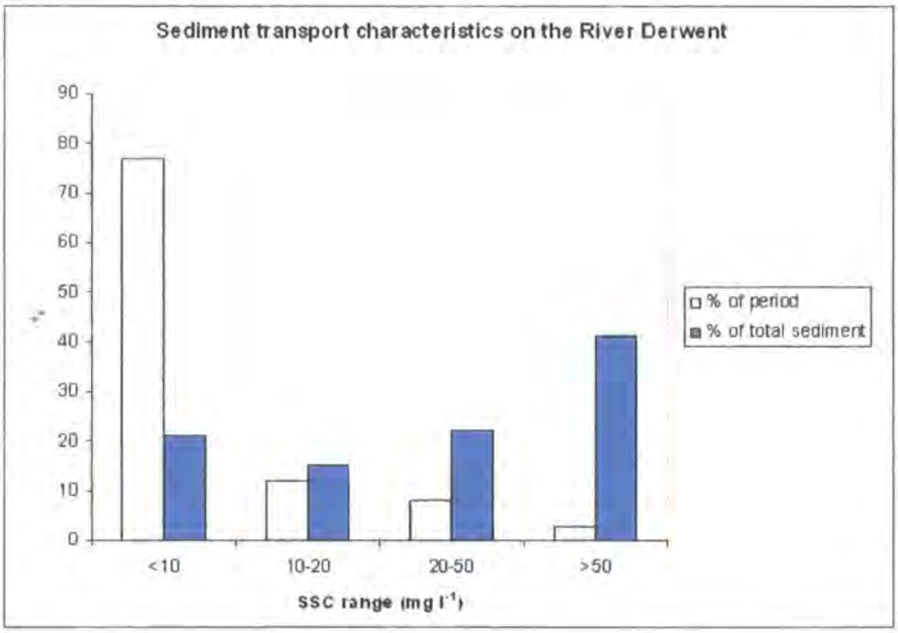

Figure 4.5: Sediment transfer characteristics on the River Derwent between April and November 2006, showing the importance of high concentrations in overall sediment transfers.

4.1.3.4 Hysteresis analysis and suspended sediment transfers during high discharge events

Hysteresis is defined by Williams (1989) as the relationships between suspended sediment concentrations (SSC) and discharge (Q) during a flow event. The nature of the SSC-Q ratio at given discharges on the rising and falling limbs is used to analyse the relationships and interations between suspended sediment transfer and river flows (Bogen 1980). Williams (1989) suggested that the nature of hysteresis depends upon the timing and amount of suspended sediment arriving at a monitoring station, the speed of the water wave carrying the sediment, and the proximity of sediment sources to the monitoring station. As a result, an analysis of hysteresis is useful in this project as it can potentially indicate likely suspended sediment sources within the Bassenthwaite Lake catchment. The converted continuous turbidity measurements between April and November 2006 at the three inflow monitoring stations comprise the raw data for the analysis below.

The two basic relationships between discharge and suspended sediment concentrations are described as positive/clockwise hysteresis (where the SSC peak arrives at the monitoring station before the discharge peak), and negative/anti-clockwise hysteresis (where the SSC peak arrives at the monitoring station after the discharge peak). On some occasions, the two peaks arrive at the monitoring station at approximately the same time, and therefore hysteresis is weak and sediment transport appears to be strongly controlled by discharge (Williams 1989). Clockwise hysteresis has been noted in catchments where dominant sediment sources are situated close to the river channel (Bogen 1980, Carson et al. 1973), and positive HI values have been associated with channel erosion (diCenzo and Luk 1997, Jansson 2002). Counter-clockwise SSC-Q relationships have been observed when dominant sediment sources are more remote, as the later arrival of the SSC peak suggests a longer sediment travel time (e.g. Hamilton 1991, Lenzi and Marchi 2000). Additionally, counter-clockwise hysteresis can occur as the result of sediment addition after the flood peak (Stott and Grove 2001). Hysteresis frequently varies over time in the same catchment. For instance, Seeger et al (2004) have observed anti-clockwise hysteresis during floods in a small catchment in the Pyrenees, Spain, as a result of large volumes of suspended sediment transported from overland flow in the catchment uplands. At other times of the year, clockwise loops dominated. Where suspended sediment concentration peaks occur after discharge peaks in anti-clockwise hysteresis events, the lag-time between the peaks is dependent upon distance from sediment sources and the efficiency of suspended sediment transport on the river (Williams 1989).

During the following analysis, the Hysteresis Index (HI) method of calculating hysteresis has been used (Lawler et al. 2006) (Equations 4.1, 4.2). This method of analysis is beneficial due to its simplicity, and the production of one data value that reflects both hysteresis direction and strength. To calculate hysteresis strength and direction, the suspended sediment concentrations on the rising and falling discharge limbs are compared at the mid-point discharge (mid-way between the discharge at the start of the flow event and the peak discharge). The two SSC values at the mid-point discharges on the rising limb (SSC_{RL}) and falling limb (SSC_{FL}) are then recorded. If $SSC_{RL} > SSC_{FL}$, then hysteresis is clockwise and the following calculation is used to work out hysteresis strength:

$$HI = (SSC_{RL} / SSC_{FL}) - 1 \quad \text{(HI value = positive)} \qquad \textit{(Equation 4.1)}$$

If $SSC_{RL} < SSC_{FL}$, hysteresis is counter-clockwise, and the following calculation is then used:

$$HI = (-1 / (SSC_{RL} / SSC_{FL})) +1 \quad \text{(HI value = negative)} \qquad \textit{(Equation 4.2)}$$

At Portinscale, Low Stock Bridge and Newlands Bridge, discharge peaks were identified in the continuous discharge record and used for the analysis below (Table 4.8). Discharge events were defined subjectively, wherever a distinct peak with a rising and falling limb was present in the discharge record and where discharge values rose c. 50% above background values close to the peak.

Date of peak discharge	Peak (Q_{max})	Start (Q_{min})	Mid-point (Q_{mid})	SSC (mg l^{-1}) at Q_{mid} on rising limb (SSC_{RL})	SSC (mg l^{-1}) at Q_{mid} on falling limb (SSC_{FL})	**Hysteresis Index (HI)**
Portinscale						
11/04/2006	25.32	10.49	17.91	11.4	7.8	**0.46**
22/05/2006	24.45	11.85	18.58	3.46	8.32	**-1.40**
22/06/2006	14.86	5.45	10.15	3.2	0.9	**2.56**
09/07/2006	7.61	2.83	5.22	3.7	3.1	**0.19**
02/09/2006	31.54	15.36	23.45	8	1.5	**4.33**
06/09/2006	32.88	19.31	26.10	5.5	7.02	**-0.28**
21/09/2006	17.08	8.00	12.54	4.05	1.9	**1.13**
28/09/2006	16.38	5.09	10.73	106.64	22.03	**3.84**
06/10/2006	38.52	15.58	27.05	24.61	11.15	**1.21**
11/10/2006	33.82	15.98	24.90	12.6	28.47	**-1.26**
22/10/2006	31.10	7.23	19.17	17.46	23.07	**-0.32**
28/10/2006	49.76	24.33	37.04	2.62	2.72	**-0.04**
11/11/2006	28.06	18.13	23.10	32.18	63.04	**-0.96**
20/11/2006	85.11	33.73	59.40	127.4	12.3	**9.36**
25/11/2006	53.47	25.44	39.46	28.6	6.5	**3.40**
Low Stock Bridge						
11/04/2006	25.32	10.49	17.91	10.1	10.6	**-0.05**
22/05/2006	24.45	11.85	18.58	20.6	33.3	**-0.62**
22/06/2006	14.86	5.45	10.15	18.1	8.3	**1.18**
05/07/2006	16.49	3.28	9.88	18.7	28.9	**-0.55**
09/07/2006	7.61	2.83	5.22	33	20.6	**0.38**
02/09/2006	31.54	15.36	23.45	11.4	3.4	**2.35**
06/09/2006	32.88	19.31	26.10	4.3	5.3	**-0.23**
21/09/2006	17.08	8.00	12.54	17.1	15.9	**0.08**
28/09/2006	16.38	5.09	10.73	8.5	7.9	**0.08**
06/10/2006	38.52	15.58	27.05	9.1	3.3	**1.76**
11/10/2006	33.82	15.98	24.90	8.8	20.3	**-1.31**
22/10/2006	31.10	7.23	19.17	9.7	7	**0.39**
28/10/2006	49.76	24.33	37.04	5.6	5.4	**0.04**
11/11/2006	28.06	18.13	23.10	6.7	12.3	**-0.84**
20/11/2006	85.11	33.73	59.40	20.3	66.1	**-2.26**
25/11/2006	53.47	25.44	39.46	20.3	38.5	**-0.90**
Newlands Bridge						
02/04/2006	13.62	4.89	9.26	27.3	18	**0.52**
23/05/2006	6.48	2.7	4.59	11.7	15.9	**-0.36**
20/06/2006	13.48	0.25	6.87	48.5	16.8	**1.89**
03/07/2006	3.68	0.3	1.99	48.4	12.9	**2.75**
09/07/2006	4.2	0.28	2.24	7.7	1.5	**4.13**
02/09/2006	14.67	2.87	8.77	12.9	10.3	**0.25**
21/09/2006	13.28	1.37	7.32	26.6	12	**1.22**
27/09/2006	12.67	0.73	6.7	30.5	11.3	**1.70**
03/10/2006	8.95	4.99	6.97	8.8	8	**0.10**
05/10/2006	11.78	3.43	7.6	5.6	7.9	**-0.41**
22/10/2006	10.75	1.15	5.95	37.8	37.4	**0.01**
26/10/2006	13.97	7.46	10.71	20.6	37.4	**-0.82**
28/10/2006	14.9	4.85	9.97	12	1.4	**7.57**
10/11/2006	15.4	0.65	8.03	33.7	8.1	**3.16**
15/11/2006	25.46	2.35	13.91	21.1	10.6	**0.99**
19/11/2006	44.12	5.14	24.63	78.7	28.5	**1.76**
24/11/2006	10.47	2.54	6.5	10.7	6.9	**0.55**

Table 4.8: Hysteresis indices for discharge events at Portinscale, Low Stock Bridge and High Stock Bridge (all figures to 2 d.p).

At the two River Derwent monitoring stations, the characteristics of hysteresis at the 16 discharge events that occurred on the river are slightly different (Table 4.8). Although the ratio between clockwise and anti-clockwise hysteresis events is similar at both monitoring stations (9 clockwise events at Portinscale compared with 8 at Low Stock Bridge), hysteresis at Low Stock Bridge tends to be much weaker than at Portinscale. The mean hysteresis index (HI) at Portinscale is 1.48, while the average HI at Low Stock Bridge is -0.03. At 11 out of 16 flow events, the Low Stock Bridge HI is closer to 0 than the counterpart index at Portinscale. In all, 69% of hysteresis indices at Low Stock Bridge have values between +1 and -1, compared with only 38% at Portinscale. The weaker, more anti-clockwise hysteresis at Low Stock Bridge suggests that SSC peaks typically occur later in discharge events than at Portinscale. This supports the characteristics of suspended sediment transport revealed in the turbidity monitoring period above, where the Low Stock Bridge peak occurs later as there is a lag time in suspended sediment transport between the two monitoring stations. Additionally, high concentrations have been observed on the receding discharge limb at Low Stock Bridge, in the form of brief pulses in SSC values.

Hysteresis at Newlands Bridge is dominated by positive HI values and therefore clockwise hysteresis (Table 4.8). HI values are above zero at 13 out of 17 discharge events, with a mean HI of 1.47, suggesting the rapid rise of sediment concentrations to peak, typically, before the maximum discharge. This may reflect the extensively modified channel form of Newlands Bridge (Figure 2.5), which has been straightened and deepened along much of its length, therefore favouring relatively fast and efficient sediment transfers.

The water sample record at all four monitoring stations supports the role of high flow events in transferring large volumes of sediment. At all four stations, the mean suspended sediment concentration of the highest 25% of discharges has been higher than that of the lowest 25% of discharges recorded at each monitoring station (Figure 4.6). At the inflow stations, the average of the highest discharges was greater than double that of the lowest discharges, although at Ouse Bridge the difference was considerably smaller.

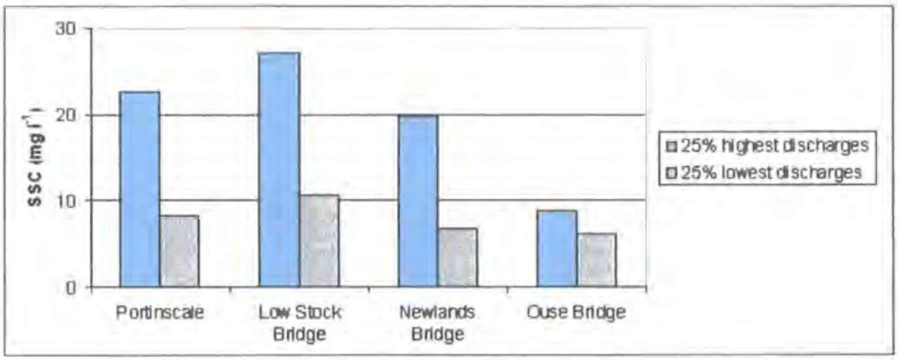

Figure 4.6: Mean suspended sediment concentrations of the water samples (2004-7) taken at the 25% highest and lowest discharges at each monitoring station.

The characteristics of large (SSC>50 mg l^{-1}) suspended sediment pulses (Figure 4.5) recorded on the River Derwent are notably different at the two monitoring stations (Table 4.9). Over the April-November monitoring period, 25 large sediment pulses were recorded at Portinscale, compared with 105 at Low

Stock Bridge. However the pulses at Portinscale were much longer on average than those at Low Stock Bridge. The mean duration of a suspended sediment pulse at Portinscale is more than 4.5 times longer than the average pulse at Low Stock Bridge; similarly, over half of the pulses at Portinscale were longer than two hours in length, compared with just a fifth of suspended sediment transfer events at Low Stock Bridge. These include an exceptionally long transfer event of nearly 39 hours on the 1st and 2nd October 2006. The Low Stock Bridge record is one of short suspended sediment pulses and therefore high variability in concentrations over relatively short periods of time, while suspended sediment delivery events at Portinscale tend to be longer with lower variations in concentrations.

	Portinscale	**Low Stock Bridge**
Number of sediment pulses (>50 mg l^{-1})	25	105
Mean length of sediment pulse (hrs:mins)	6:05	1:20
% of pulses of duration<1 hour	28%	69.5%
% of pulses of duration>2 hours	56%	20%
Longest three sediment pulses (hrs:mins)	38:45 (01-02/10/06) 12:30 (04/10/06) 11:15 (27-28/09/06)	15:30 (20/11/06) 11:00 (05-06/07/06) 7:30 (24/08/06)

Table 4.9: Summary of the characteristics of suspended sediment transport events on the River Derwent monitoring stations.

In some cases, an SSC peak at Portinscale is followed by a second SSC peak of similar magnitude and duration at Low Stock Bridge (Figure 4.7). This suggests that a wave of sediment is being transported down the river, frequently following a flow event (Figure 4.7). In such cases, a lag time of 1-2 hours has been observed between the sediment pulse arriving at Portinscale and registering at Low Stock Bridge, 3.7 km downstream (Table 4.10).

Turbidity event peak date	Portinscale NTU peak	Low Stock Bridge NTU peak	Lag time (hrs:mins)
11th April	13:00	15:00	2:00
5th July	21:15	23:00	1:45
6th September	09:45	11:30	1:45
11th November	19:30	21:00	1:30
19th November	00:00	01:00	1:00

Table 4.10: Lag times for suspended sediment transfer events during continuous turbidity monitoring, April-November 2006. NTU = Nephlometric turbidity unit.

The turbidity records of such events suggest that the rising SSC limbs at both sites are similar in gradient, and the peak sediment concentrations are approximately equivalent (e.g. Figure 4.7). However during some flow events the Low Stock Bridge record indicated an increased suspended sediment load between the two monitoring stations. Good examples of such events include a large discharge in November 2006 (Figure 4.8). On the 20th November, a large flow event was recorded at Portinscale gauging station, with a peak discharge of 85 m^3 s^{-1} at 02:45. A sediment pulse associated with this rise in flow was observed at both monitoring stations just before the peak discharge. Peak concentrations of 304.8 mg l^{-1} (Portinscale, number 1 on Figure 4.8) and 381.5 mg l^{-1} (Low Stock Bridge, number 2) were recorded an hour apart at 00:00 and 01:00 respectively. Suspended sediment transfers were notably different at the two stations during the falling discharge limb. At Portinscale, suspended sediment concentrations declined smoothly and rapidly from the peak discharge.

The Low Stock Bridge record suggests that, converse to this decline, five short-lived, rapid rises in suspended sediment transport were recorded (3). Five of these additional peaks have concentrations above 200 mg l^{-1}. One of the peaks was higher than the peak in concentrations at the time of the discharge event, recording 436 mg l^{-1} at 05:00. The longest such rise in concentrations was just over 1 hour long. As the suspended sediment peaks were not observed at Portinscale, and there are no indications of rises in discharge at the time of such peaks, it is suggested that they represent the rapid supply of large volumes of sediment to the channel between the two monitoring stations. Following the peaks, suspended sediment concentrations remained elevated (30-60 mg l^{-1}) for a period of c. 15 hours (4). It is likely that further sediment addition occurred during this period, although in this case, fine sediment delivery to the channel was relatively slow over a longer period of time. This may represent the reworking of recently eroded sediment within the river channel.

The pattern of contrasting suspended sediment transport at the Derwent monitoring stations also occurred during September 2006 (Figure 4.9). In this case, a relatively small flow event with a peak discharge of 17 $m^3 s^{-1}$ led to a moderate suspended sediment pulse at Portinscale with a peak of 31.6 mg l^{-1} (number 1 on Figure 4.9) before concentrations declined to fluctuating single-digit concentrations. At Low Stock Bridge, suspended sediment concentrations were elevated before the discharge peak (2) and there is no evidence of a rise in suspended sediment transport following the discharge peak. On the falling discharge limb, seven brief pulses of suspended sediment were recorded (3), with all peaks in excess of 40 mg l^{-1} and lasting no more than half an hour. The peaks are similar to those observed in the November flow event as they are independent of discharge and/or suspended sediment transport at Portinscale. Therefore, it is again likely that they represent brief 'injections' of suspended sediment to the channel. Peaks in suspended sediment transport at Low Stock Bridge have also happened when flow events have not occurred. This is shown by a set of fluctuating moderate-high concentrations at the end of June 2006 (Figure 4.10), where SSC values peaked above 30 mg l^{-1} on 13 occasions over a two-day period, despite concentrations remaining consistently below 10 mg l^{-1} at Portinscale and the fact that a flow event had not occurred during the period. Interestingly, the more variable nature of the Low Stock Bridge record was also observed in the river water sampling on 2nd September 2006 (Section 4.1.3.1, Figure 4.3). It is possible that these extremely short-lived suspended sediment pulses are the result of the addition of small volumes of sediment from sources close to Low Stock Bridge, potentially from sediment poaching and run-off from the watering point upstream of Low Stock Bridge, which has been observed to occur following rainfall (Figure 4.11). Therefore, sediment addition had taken place between the two monitoring stations on the River Derwent independent of increases to background suspended sediment load and river discharge increases.

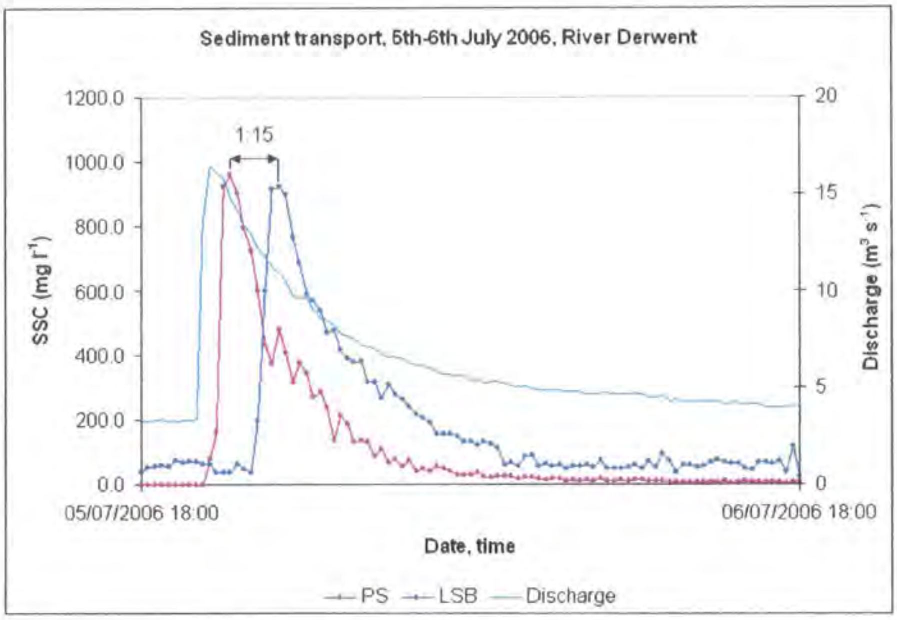

Figure 4.7: A large suspended sediment pulse observed between the 5th and 6th July 2006 at Portinscale and Low Stock Bridge. The discharge values (peak: 16.4 $m^3 s^{-1}$) and sediment transport peaks at Portinscale and Low Stock Bridge are shown, as is the lag time (1 hour 15 minutes) between the peak sediment transport at the monitoring stations.

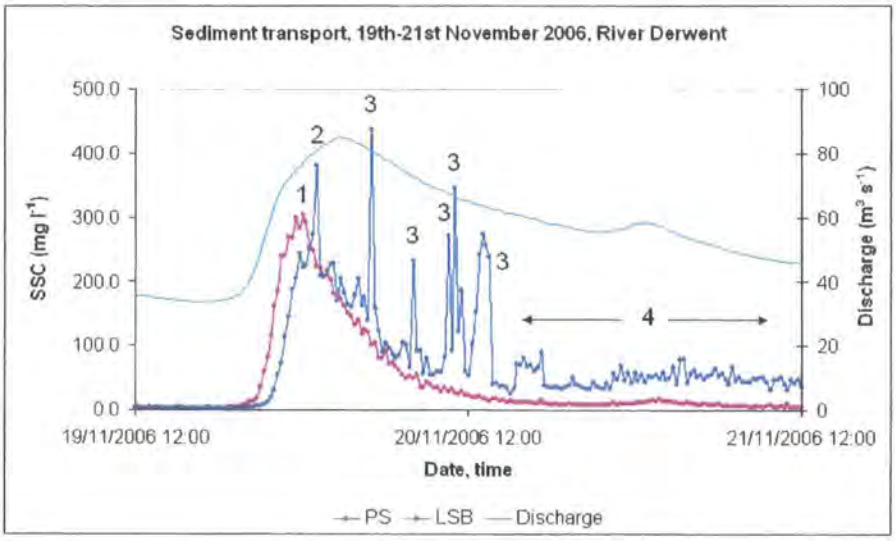

Figure 4.8: Suspended sediment transfers on the River Derwent at Portinscale and Low Stock Bridge, 19th-21st November 2006. As with Figures 4.9 and 4.10 below, numbers on the graph are referred to in the text in Section 4.1.3.4.

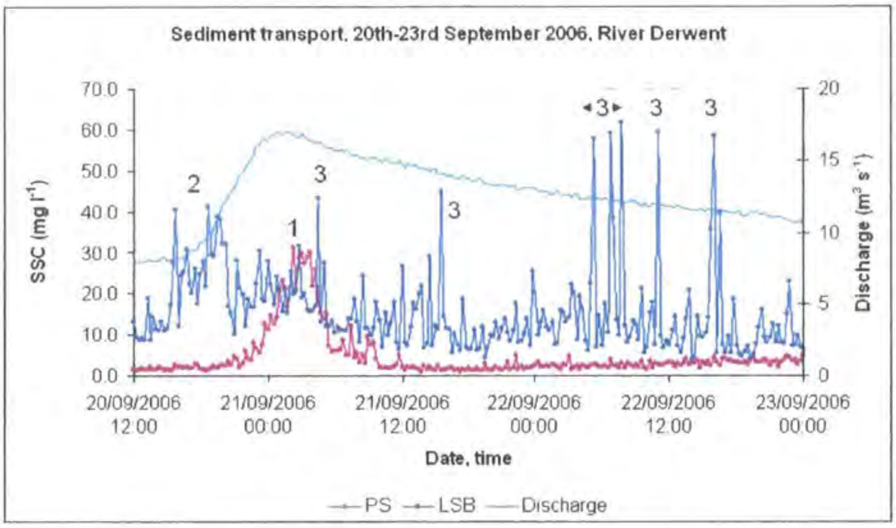

Figure 4.9: Suspended sediment transfers on the River Derwent at Portinscale and Low Stock Bridge, 20th-23rd September 2006.

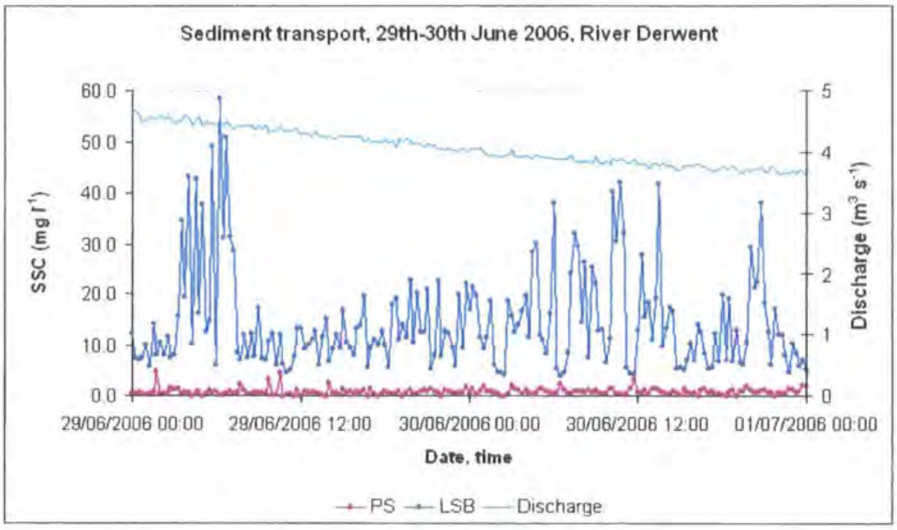

Figure 4.10: Suspended sediment transfers on the River Derwent at Portinscale and Low Stock Bridge, 29th-30th June 2006.

Figure 4.11: Suspended sediment addition to the River Derwent from an area of bare soil in the large poaching scar c.150 m upstream of Low Stock Bridge (NY 244 257) following heavy rain, 22nd June 2007.

It is highly possible that the suspended sediment peaks observed in the above two events represent river bank failures. The rapid addition of large volumes of sediment that occurs during large bank failure events (Section 2.4.2) would support to the dramatic, brief rises in sediment transport observed. Additionally, the position of such peaks on the falling discharge limb would support river bank erosion, which often occur during declining river flows as 'draw-down' failures (Section 2.4.3). Alternatively, other sources of the suspended sediment delivery include small streams and field drains. As many of the sediment transport peaks are represented only at Low Stock Bridge and not at Portinscale (e.g. Figures 4.8, 4.9, 4.10), the source of such sediment peaks must be the lowland River Derwent between the two monitoring stations, and not the upland catchment. These patterns of suspended sediment transport at Portinscale and Low Stock Bridge are also supported by the analysis of sediment pulse magnitude/frequency (Table 4.9), which suggests that suspended sediment transfer events at Low Stock Bridge are more numerous and shorter on average than those at Portinscale.

4.1.4 Summary and conclusions

It is clear that suspended sediment transfers to Bassenthwaite Lake occur predominantly during relatively infrequent high flow events, during which high suspended sediment concentrations were recorded. This is demonstrated in the overall mean concentrations of water samples taken from the four monitoring stations (Section 4.1.3.1, Table 4.3) and the characteristics of the turbidity record (Section 4.1.3.3). The importance of such high-magnitude, low-frequency events to overall sediment transport is well known (e.g. Thompson and Oldfield 1986, Walling and Webb 1987).

Support is also given to the presence of considerable sediment storage in the lake basin. This is suggested by the relatively low amount of suspended sediment recorded leaving the lake at Ouse Bridge, compared with the average sediment inputs at Low Stock Bridge and Newlands Beck, revealed from the water sample record (Section 4.1.3.1, Table 4.3). It is likely that the attenuating and storage effects of the lake, especially a long residence time of 19 days (Reynolds 1999), means large suspended sediment inflows do not translate to immediate outflows.

Based upon the average suspended sediment concentrations of the inflow monitoring stations (Section 4.1.3.1) and overall suspended sediment loads (Section 4.1.3.2), the dominant source of suspended sediment to Bassenthwaite Lake is the River Derwent. The total suspended sediment load carried by the Derwent during the 8-month turbidity monitoring period in 2006 was 4,077 t, compared with an 807 t load carried by Newlands Beck. This reflects a greater suspended sediment productivity (per unit area) of the catchment (Table 4.7) as well as a larger overall catchment area and a higher transport capacity resulting from a higher annual discharge (Hall et al. 2001). Although higher discharges on the River Derwent were slightly more prevalent during the turbidity monitoring period than across the long-term discharge record (Figure 3.5), the above characteristics of the River Derwent and its catchment mean that it would be expected to dominate suspended sediment supply to Bassenthwaite Lake over longer periods. There is no support for the hypothesis of Hatfield and Maher (2006) which identified Newlands Beck as the most important suspended sediment input to the lake. The suspended sediment concentrations recorded in this study suggest that Newlands Beck plays only a minor role in suspended sediment transfers to Bassenthwaite Lake.

The difference between the suspended sediment concentration records of the two monitoring stations on the River Derwent is especially significant, in suggesting likely sediment sources. Over the 2004-7 monitoring period and water sample record (Section 4.1.3.1), the downstream station (Low Stock Bridge) recorded a higher mean concentration and a greater variability and range of concentrations. This is supported by the 772 t increase in overall sediment load at Low Stock Bridge (Table 4.6), as indicated in the 8-month turbidity monitoring period. This suggests that the change in storage in the catchment sediment budget (Section 3.1) is considerable, and sediment addition is contributed in the lowland areas of the River Derwent between the two monitoring stations. The differing nature of suspended sediment transport at the two stations further supports this hypothesis (Section 4.1.3.3, 4.1.3.4), as suspended sediment transfers at Low Stock Bridge have been seen to occur during brief rises to high concentrations, which are not represented at Portinscale, where single-peaked response to flow rises dominate. The importance of such events in suspended sediment transport at Low Stock Bridge is suggested in the hysteresis analysis (Section 4.1.3.4), where sediment peaks often occurred later relative to discharge peaks than at Portinscale (e.g. Figures 4.8, 4.9, 4.10). It is suggested that suspended sediment transfers at Portinscale largely reflect sediment delivery from the upper catchment, while the suspended sediment peaks observed at Low Stock Bridge are a result of the addition of sediment in short events on the lowland River Derwent between the two monitoring stations. It is possible that these events are caused by river bank failures, which typically transfer large volumes of sediment to the river channel almost instantaneously. Furthermore, the spatially-limited nature of the sediment addition in an area of widespread river bank erosion strongly implies that the bank erosion is the main source of suspended sediment, especially given the absence of significant fluvial inputs on the lowland River Derwent. The following section will assess the potential for river bank erosion to contribute to fine sediment inputs on the River Derwent (Section 4.2).

Based upon the extrapolated annual estimates of suspended sediment loads at Low Stock Bridge and Newlands Bridge (Table 4.6), it is estimated that over a 12 month period, 7,327 t of suspended sediment is transferred to Bassenthwaite Lake from the River Derwent and Newlands Beck. Based upon comparisons of mean water sample suspended sediment concentrations between inflow and outflow monitoring stations, (Section 4.1.3, Table 4.3), the estimated annual suspended sediment outflow at Ouse Bridge is 2,858 t. Lake sediment storage can therefore be approximated at 4,469 t over 12 months. Given a lake area of 5.28 km^2 (Reynolds 1999), this suggests an average annual sedimentation rate in Bassenthwaite Lake of 0.08 g cm a^{-1}. This rate is comparable with several published estimates of sediment deposition rates from sediment cores retrieved from Bassenthwaite Lake (Section 1.4). However, as sediment deposition is known to be uneven in water bodies, with higher deposition rates in deeper, lower velocity areas (Håkanson and Jansson 2002), sediment deposition in some sectors of Bassenthwaite Lake could be considerably greater. In addition, unquantified autochthonous sources in Bassenthwaite Lake and suspended sediment transfers from unmeasured small streams may increase the sedimentation rate further.

4.2 Assessment of river bank erosion on the lowland River Derwent between Derwent Water and Bassenthwaite Lake

This section describes the nature of river bank erosion occurring on the River Derwent between Derwent Water and Bassenthwaite Lake, and the potential for it to contribute to the Bassenthwaite Lake catchment's sediment budget. Recent observations and field assessments (Section 2.2) suggest high sediment delivery risks in this area, with a strong possibility that river bank erosion constitutes a significance source of sediment in the Bassenthwaite lowland catchment. Furthermore the literature review of river bank erosion processes (Section 2.4) suggests that active river bank failures and extensive bank erosion have the potential to deliver a large volume of sediment to the river and the catchment's sediment budget. Here, the mapping of river bank erosion features on the Derwent (Figure 4.12, Section 4.2.1) is used to assess the extent of river bank erosion (Section 4.2.2), as well as the relationship between bank erosion and historical channel activity (Section 4.2.3). The composition (Section 4.2.4) and morphology (Section 4.2.5) of eroded river banks are also described. A detailed assessment of the extent and morphology of actively eroding river banks follows (Section 4.2.6), which is compared with the morphology of semi-active river banks (Section 4.2.7). Sediment delivery risks from poaching scars (Section 4.2.8) and from river bank weakening/preparation processes (Section 4.2.9) are described. The findings of the laser scanner survey of river bank erosion rates and bank morphological change (Section 3.3.2) is summarized in Section 4.2.10. Finally, a brief overview of the bank management techniques currently in use on the River Derwent (Section 4.2.11) is presented before the chapter summary (Section 4.2.12).

4.2.1 River bank erosion map of the River Derwent

The map of river bank erosion on the River Derwent (Figure 4.12) was compiled from a GPS survey (Section 3.3.1). Therefore, it shows the extent of erosion in Spring (May-June) 2007. Indicated on the map are lengths of eroded river banks and poaching scars. Boulder revetments and bridges are also mapped, to indicate their distribution.

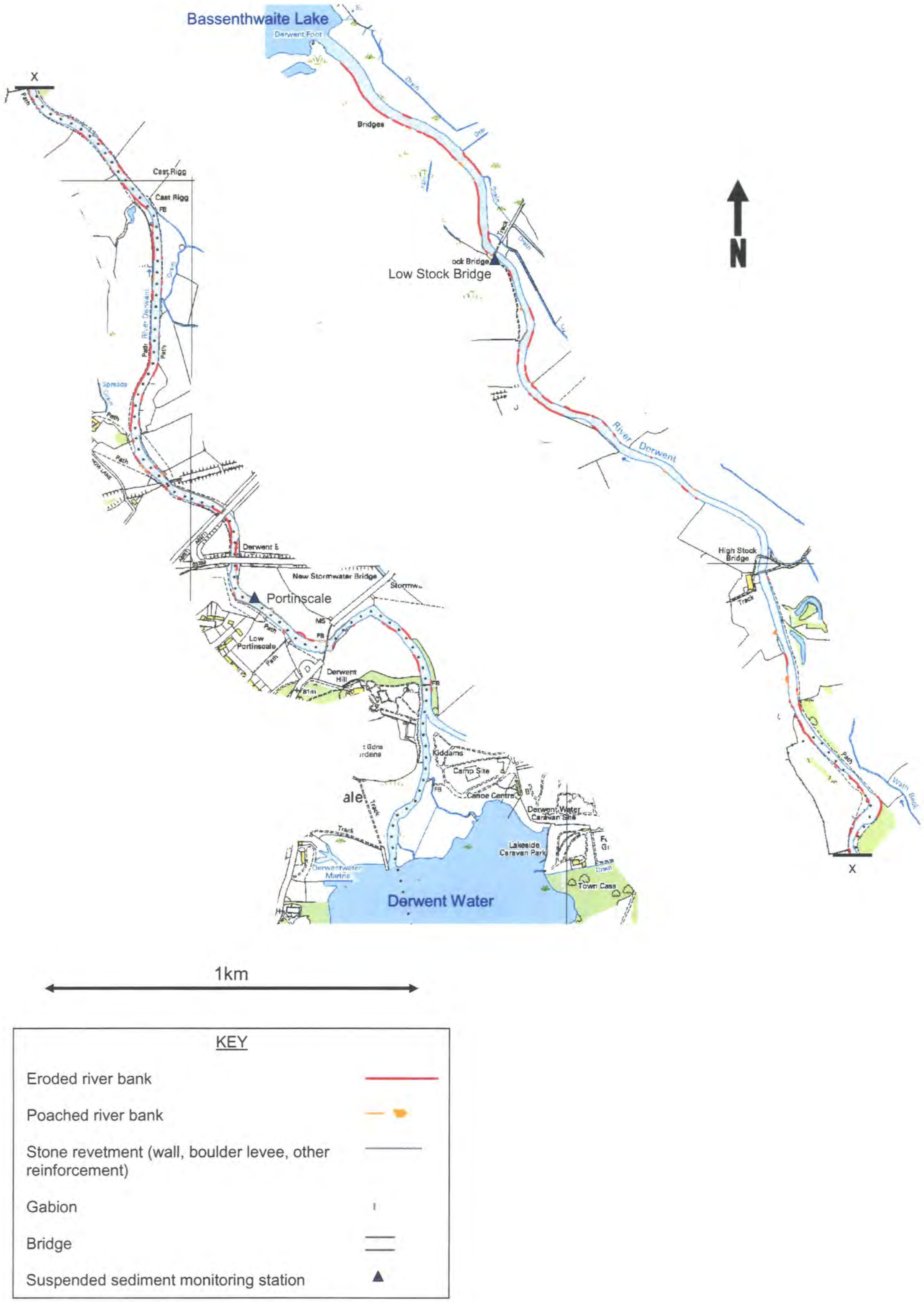

Figure 4.12: Map of eroded river banks on the River Derwent between Derwent Water and Bassenthwaite Lake.

4.2.2 Extent and distribution of river bank erosion on the River Derwent

In total, 21.1% of the River Derwent's banks are assessed as eroded, with 78.9% of banks not eroded (Table 4.11). Some 19.2% of river banks are typical exposed river bank faces as an apparent result of fluvial erosion, while 1.9% of banks are poached (eroded by grazing animals). Significantly, 9.4% of the banks had features which suggested that erosion was presently active, and that material was being transferred to the channel in the form of block failures. The fact that over 2.4 km of banks are eroded on the River Derwent, over 40% of which are actively eroding at the time of survey, suggests that river bank erosion has the potential to be a significant source of sediment in the lowland Bassenthwaite catchment, and therefore a potentially important sediment input to Bassenthwaite Lake itself.

Category	**Length of banks in category (m)**	**Proportion of overall River Derwent bank length (11,400 m) (%)**
Not eroded	8,998	**78.9**
Eroded	2,188	**19.2**
(Actively eroding)	*(980)*	***(9.4)***
Poached	214	**1.9**
All eroded banks	**2,402**	**21.1**

Table 4.11: The extent of eroded river banks on the River Derwent, Spring 2007.

The river bank erosion map (Figure 4.12) suggests that eroded river banks are distributed unevenly throughout the River Derwent's lowland channel. Significant areas of river bank erosion are located between the A66 road bridge

(NY 251 241) and High Stock Bridge (NY 243 259), and on the west bank of the Derwent downstream of Low Stock Bridge (NY 236 268). These extensive areas of river bank erosion are shown on Figure 4.13 as the rapid increases in the gradient of cumulative river bank erosion between 2-3 km and downstream of 5 km respectively. Conversely, some reaches of the Derwent are notably stable with sparse or absent bank erosion, e.g. the c. 800 m reach downstream of High Stock Bridge. Such reaches are shown as horizontal plateaus on the cumulative erosion graph (Figure 4.13). Figure 4.13 also shows that river bank erosion is considerably more extensive on the west bank of the River Derwent (total erosion = 1,580 m) than on the east bank (822 m). This difference is largely a result of the extensive erosion downstream of Low Stock Bridge, which is overwhelmingly concentrated on the west bank (Figure 4.12). This is shown by the greater gradient of the cumulative erosion line graph for the west bank of the Derwent from 5 km downstream to Bassenthwaite Lake (Figure 4.13). An important reason for the uneven distribution of bank erosion on the Derwent is the pattern of historical river activity and channel change (Section 4.2.3), which shows significant channel migration in several areas of the river.

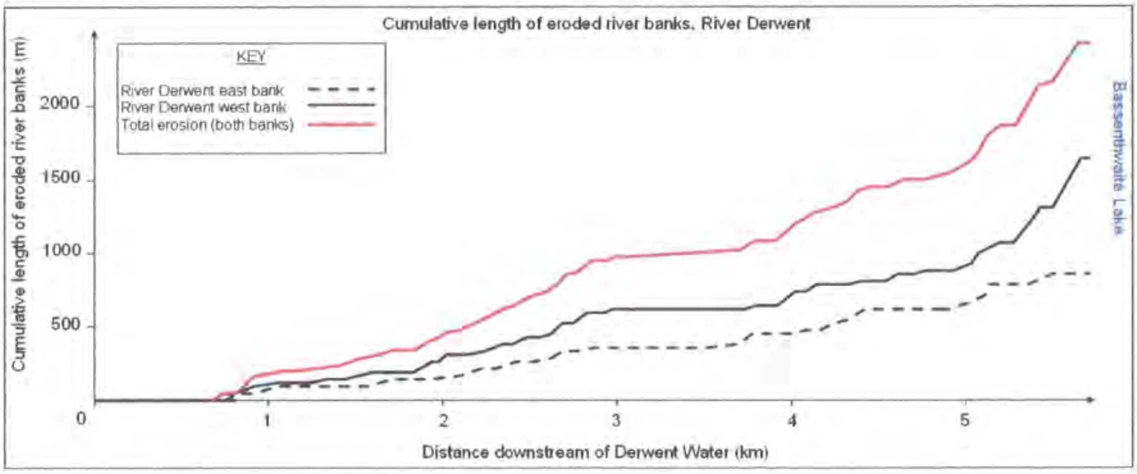

Figure 4.13: Cumulative lengths of eroded river banks on the River Derwent between Derwent Water and Bassenthwaite Lake.

4.2.3 A comparison of historical channel change and river bank erosion

A comparison of the River Derwent's course on historical and contemporary maps (Section 2.2.3) provides evidence for the presence of river bank erosion along certain reaches of the River Derwent. Significant changes in channel position between the 1863-7 County Series mapping and contemporary map data suggests that the channel has been active and that bank retreat, and therefore bank erosion, has taken place. A comparison of the two maps between How Farm and High Stock Bridge (Figure 2.9) suggests several areas of channel position change, which were identified in Section 2.2.3. Figure 4.14 shows a comparison of the position of the River Derwent on a 2 km reach between Portinscale and High Stock Bridge on six maps released between 1863 and 2007. This mapping comparison (Figure 4.14) suggests that much modern-day bank erosion is occurring in areas of significant channel migration. For instance, the lengthy sections of river bank erosion on the west bank upstream of How

Farm near the south of the section (at meanders 1 and 2 on Figure 4.14) are situated in an area where the channel planform has changed and migration has occurred, leading to river bank erosion. At both meander 1 (NY 248 244) and 2 (NY 249 249), there is evidence of active river bank failure (Section 4.2.5). River bank erosion is extensive and active in particular on the outside banks of the two meanders upstream of High Stock Bridge at NY 246 253 (3) and NY 244 255 (4), where a clear shift in the channel position has occurred (Figure 4.14). Aside from this central section of the river, the extensive, actively-eroding river banks near Derwent Foot (NY 232 272, Figure 4.12) are located at an area of significant channel migration (Section 2.2.3). Therefore, it is likely that large historical channel form changes are a contributing factor towards current river bank erosion.

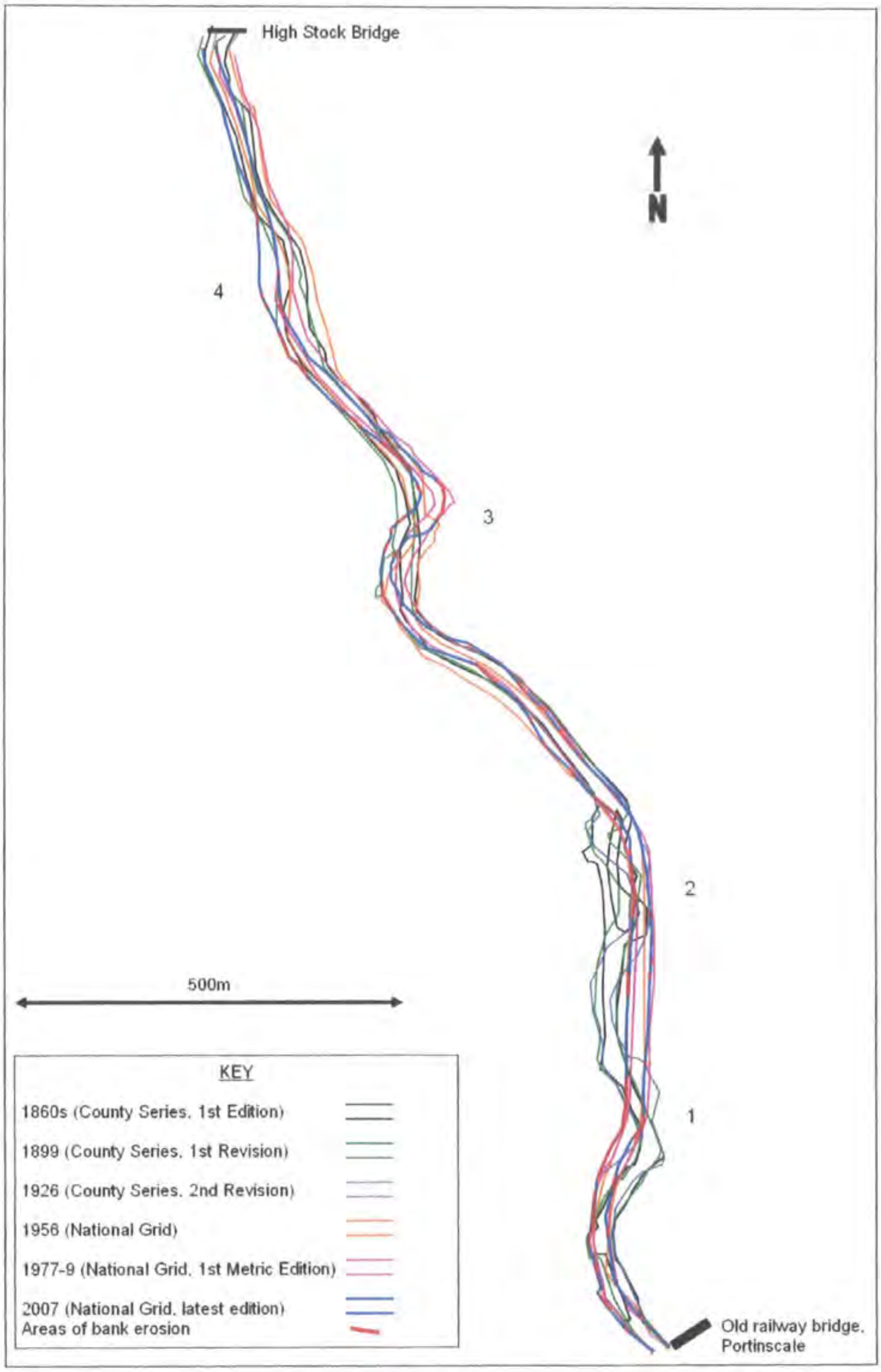

Figure 4.14: The relationship between modern-day river bank erosion and areas of significant river channel migration, on a reach of the River Derwent between Portinscale and High Stock Bridge. Numbering corresponds to bank areas referred to in the text (Section 4.2.3).

4.2.4 Composition of eroded river banks

The banks of the River Derwent are typically composed of an upper layer of cohesive clay and silt, and a lower, non-cohesive layer of coarse gravel. The lower, non-cohesive layer was found to occur at varying elevations on the river banks. This means considerable variations in river bank composition can occur over relatively short distances. A good example of this is on the west bank of the Derwent, upstream of Low Stock Bridge, where the exposed west bank (NY 236 267) is predominantly non-cohesive. Upstream of this, the gravel layer declines in elevation, and within c. 100m it is at the elevation of the river bed, rendering the bank above it entirely cohesive (e.g. at NY 236 264) (Figure 4.15). This short section is representative of changes in bank composition along the Derwent as a whole. Eroded sections near Portinscale are generally composite in form with a thick non-cohesive layer, while the lengthy eroded sections between High Stock Bridge and Low Stock Bridge are predominantly made up of cohesive fine sediment. At the extremes of the river close to Derwent Water and Bassenthwaite Lake, the banks are mostly cohesive. Composite river banks are important in the generation of overhangs on the upper bank, as undercutting regularly occurs at the lower, more easily-eroded lower bank (Section 2.4.2.1). For instance, at the eroded bank at Portinscale described below (Figure 4.21) (NY 252 238), the maximum undercut is situated at an elevation of 1.68 m on the bank face, near the boundary of the cohesive and non-cohesive material layers. Therefore the composite bank structure favours bank instability and therefore increased sediment delivery risks.

Figure 4.15: Comparison of river bank composition between High and Low Stock Bridges: a composite bank with a thick non-cohesive layer (left), and an almost completely cohesive bank (right).

4.2.5 Geometry and morphology of eroded river banks on the River Derwent

The geometry of a river bank plays a major role in its stability, in particular the river bank's height and gradient (Section 2.4.1). Higher, steeper river banks are generally more susceptible to erosion, particularly by cantilever and rotational failure mechanisms (Section 2.4.2). Furthermore, the presence of an undercut bank profile means that the material above the overhang has the potential to collapse directly into the channel. During fieldwork, 77 bank profiles were measured on the River Derwent at eroded river banks between Derwent Water and Bassenthwaite Lake (Section 3.3.1) at representative eroded bank sections. These measurements are used to assess the characteristics of eroded banks on the River Derwent and the potential of bank erosion for sediment delivery at eroded bank sections.

The average bank height of all 77 eroded bank sections surveyed was 1.42 m, with the mean bank angle just over 69°. Among the eroded banks, there are considerable variations in bank height (Figure 4.16). Over two-thirds of all bank profiles were above 1 m in height (55 of the 77 banks), but less than a fifth of eroded sections were in excess of 2 m high. The highest bank recorded in the survey was 3.5 m in height. As may be expected, eroded river banks on the Derwent tended to have steep gradients. Only five bank profiles out of 77 were below 45°, while nearly a third (31%) of all banks had very steep profiles above 80°. Five banks were measured as being of 90° or greater, suggesting a vertical bank face or overhang development. It is interesting to note that no overall trend exists between bank height and bank angle, reflecting the fact that, despite varying bank heights, the vast majority of eroded banks are relatively steep. This characteristic results from the nature of erosion processes (erosion of the lower bank, removal of material from the bank face and undercutting) which leads to higher gradients, compared with non-eroded banks.

The vast majority of eroded river bank profiles (88%) showed some undermining of a portion of the river bank. Of the banks that were undercut, the mean maximum undercut depth (into the bank underneath the overhang) was 280 mm. However, over four-fifths of overhanging bank profiles had undercut depths lower than 300 mm. The mean undercut depth is somewhat biased by a few bank profiles with very large overhangs, especially four banks with undercut depths greater than 700 mm.

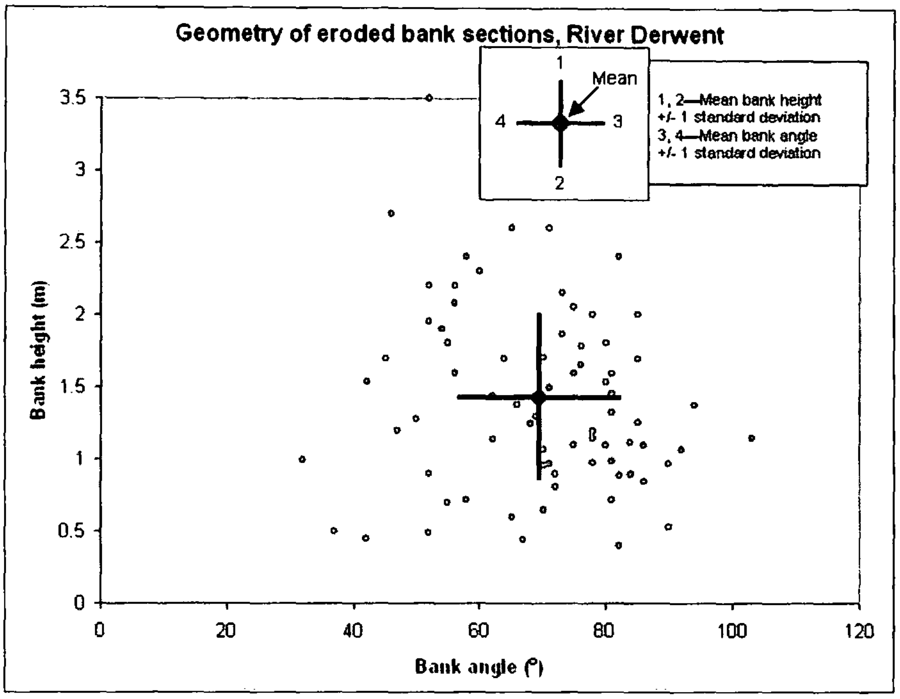

Figure 4.16: The geometry of eroded bank sections measured on the River Derwent, showing average geometry and centroids.

4.2.6 The form of actively eroding river banks on the River Derwent

Out of the 77 profiles recorded at eroded banks, 23 profiles were taken on river banks that were currently undergoing active erosion, as indicated by the presence of failed blocks at the foot of the bank. Other evidence of active erosion includes the presence of tension cracks at the bank top (suggesting imminent block detachment in the event of further bank retreat) and the undermining of structures on the upper river bank (e.g. fences). In other reaches, river banks are obviously eroded, as they have a bank face composed of exposed soil. However, the banks themselves do not have features suggesting recent sediment delivery to the channel and appear relatively stable. 54 profiles fell into this latter category. It is important to note river bank erosion and sediment delivery may well occur at a presently stable eroded bank, and for this reason these 54 profiles are referred to as 'semi-active' river banks. The analysis of river banks presently undergoing active erosion is very important to the aims of this project, as such banks represent areas of current sediment delivery.

4.2.6.1 The geometry of actively eroding river banks on the River Derwent

In general, actively eroding river banks on the River Derwent are consistently steeper than semi-active river banks. The average profile angle of eroding banks is 12.8° steeper than that of stable/semi-active banks (Table 4.12) which is seen by the clustering of actively eroding banks at steeper gradients (Figure 4.17). Of the 24 bank profiles with mean angles greater than 80°, 54% are eroding; by contrast, only 19% of profiles below 80° are eroding. Furthermore, the maximum undercut is typically slightly greater in depth on eroding river banks by 11 mm. These observations are consistent with the theory present in the literature review on bank stability, which suggests that steeper river banks are less stable (Section 2.4.1) and more prone to larger bank failures (Section 2.4.2).

Bank type	Height (m)	Angle (°)	Maximum undercut (mm)
Semi-active			
mean	1.45	65.6°	278
standard deviation	0.70	14.5°	145
Actively eroding			
mean	1.37	78.4°	289
standard deviation	0.46	10.7°	184

Table 4.12: Summary of the geometry of actively eroding and semi-active river bank profiles.

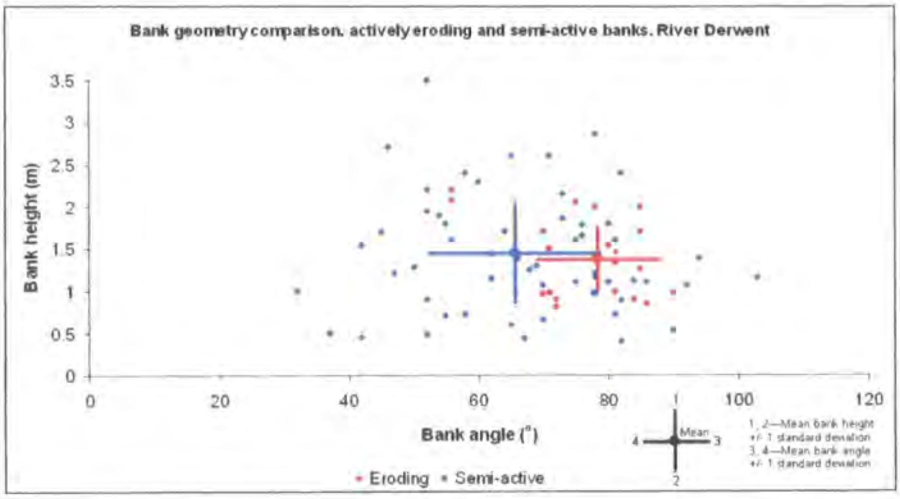

Figure 4.17: Geometry comparison of presently actively eroding and semi-active banks profiles showing average geometry with centroids for both categories.

Although an increase in river bank height generally has a negative influence on river bank stability (e.g. Lohnes and Handy 1968, Brunsden and Kesel 1973, Thorne 1982, Osman and Thorne 1988, Section 2.4.1), several high banks on the River Derwent are at present relatively stable and conversely several relatively low river banks are actively eroding. Indeed, actively eroding banks are, on average, very slightly lower than semi-active banks (Table 4.12).

4.2.6.2 Extent and morphology of actively eroding river banks on the River Derwent

Actively eroding river banks (those undergoing bank failure at the time of survey) are distributed throughout the length of the River Derwent (Figure 4.18). The total length of river banks with evidence of active erosion was 980 m, accounting for 9.4% of the total length of the River Derwent's banks (Table 4.11). Active river bank erosion is distributed unevenly along the River Derwent, although the most extensive block failures are occurring on the west bank of the Derwent downstream of Low Stock Bridge, and on several banks between Portinscale and High Stock Bridge. This section aims to describe the morphology of these banks, and the evidence for active erosion.

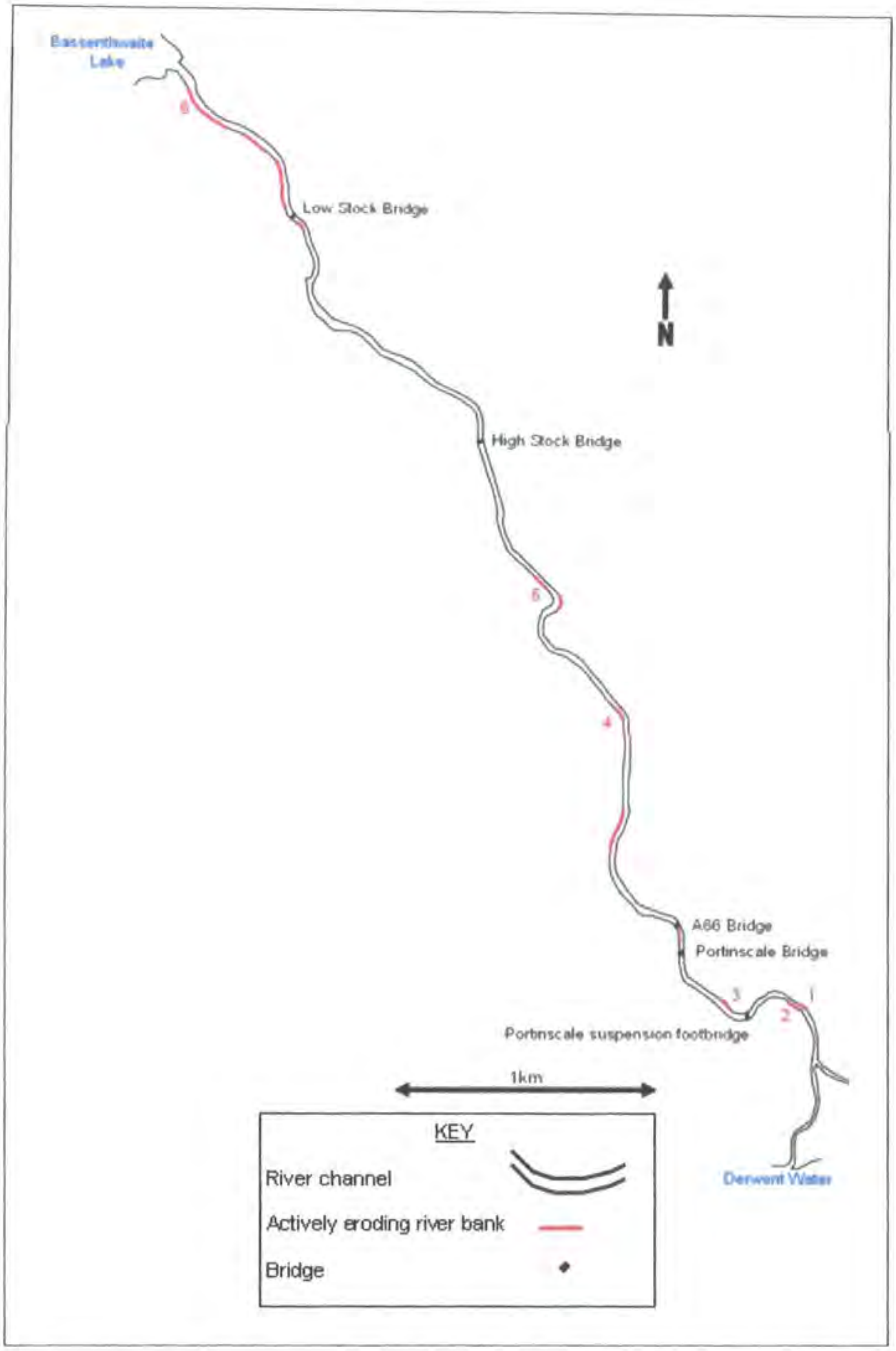

Figure 4.18: Map of the River Derwent channel between Derwent Water and Bassenthwaite Lake, highlighting the bank lengths currently in the process of active erosion (block failures). Numbered bank reaches are used as examples in the text below.

The river banks near Portinscale suspension footbridge (NY 252 238) are notable for some lengths of active river bank erosion and large block failures. Upriver of the bridge are two bank lengths with block failures. Bank 1 (Figure 4.19) is a 47 m cohesive section on the outside (east bank) of the slight meander at NY 255 238. The bank features several large failed blocks at the bank foot, many in excess of 1 m^2 in size. Active erosion is also indicated by an extensively undermined banktop fence and the presence of tension cracks at the bank top. The bank is above 2 m in height and has a relatively low angle of 56°, and is composed entirely of fine-grained, cohesive material. However, a key component in the bank's extensive block failures is the significantly undermined upper bank, with a very large maximum undercut depth of 700 mm. Some of the failed blocks are slab-shaped and have their tops facing upwards, resting against the bank face. This suggests that the blocks had slumped downwards along a failure plane at the back of the block, suggesting rotational failure (Section 2.4.2.2). Downstream of this bank on the opposite side of the channel is bank 2 (Figure 4.20), where several small blocks of cohesive material were found at the base of the bank. The 42 m section of bank has a steep overall gradient of 85° and a large undercut of 340 mm, a morphology which has contributed to the block failures occurring at the bank.

Figure 4.19: Bank 1 (East bank, NY 255 238, river flow right-left).

Figure 4.20: Bank 2 (West bank, NY 255 237, looking downstream).

Approximately 80 m downstream of Portinscale suspension bridge is a 49 m eroded bank section (bank 3, NY 252 238) (Figure 4.21). The river bank is a classic high (maximum height = 2.08 m) composite river bank, with an upper layer composed of fine-grained silt and a lower layer of gravels. The river bank face has undergone several changes in form, as high river flows have eroded the talus slope at the bank foot and caused retreat of the lower bank, causing oversteepening (Figure 4.22). Active block failures have been observed on the bank throughout the course of the fieldwork, with the frequent delivery of cohesive material from the upper bank to the bank foot (Figure 4.23). Much of the upper bank is therefore considerably undermined, with extensive overhang development and turf slippage. The maximum undercut depth is 700 mm, suggesting considerable instability of the upper bank. Therefore, significant undermining of the upper bank is the key destabilising influence on this bank.

The composite river bank structure, which favours high erosion rates on the lower bank (Section 2.6.2.2), is also a contributing factor towards bank failures.

Figure 4.21: Bank 3 (East bank, NY 252 238, river flow right-left).

Figure 4.22: Considerable undercutting (indicated) at bank 3 following a rise in river levels, also note the oversteepened profile of the lower bank.

An example of the active nature of block failures occurred during early 2007 (Figure 4.23). On the 19th February 2007, a photograph of the eroded bank section showed several failed blocks of material resting on the lower bank and on the river channel edge. However, when the bank was photographed on the 5th March 2007, the failed blocks were no longer present at the base of the bank, and had been entrained by a rise in river levels. Significantly, the lower (non-cohesive) bank is much steeper than in the photograph taken on the 19th February. It is likely that the rise in river flows eroded the base of the bank, creating a steeper profile and undercutting. A photograph taken of this river bank six days later on the 11th March 2007 shows that a fresh failure had occurred, as large blocks of cohesive material had collapsed from the upper bank and were resting on the lower bank. These observations suggest active cantilever failures.

Figure 4.23: Block failure events and material removal from bank 3 near Portinscale suspension footbridge (looking upstream). Photograph dates: Top - 19th February 2007, middle – 5th March 2007, bottom – 11th March 2007.

Between Portinscale and High Stock Bridge, many of the actively eroding river banks have relatively low heights. A good example of such a bank was found on the west bank of the Derwent in a 47 m section upstream of NY 248 249 (bank 4, Figure 4.24). The bank is only 0.85 m in height but features both a very steep overall gradient (86°), and the maximum undercut is situated at a low elevation at only 0.19 m above the bank foot. Therefore, a large proportion of the bank is undermined which has rendered the bank susceptible to cantilever failures, which are suggested by the presence of fallen vegetated blocks at the bank foot. A further low, actively eroding river bank is located on the west bank to the south of the sharp meander at NY 243 259, where a 60 m eroding bank reach is found at NY 245 254 (bank 5, Figure 4.25). Several vegetated blocks were found at the base of this river bank during surveying. The bank is low (height<1 m throughout the bank length), and is similar in morphology to bank 4 as a large proportion of the river bank is undermined, with a maximum undercut at a low elevation on the bank face (measured between 0.1-0.3 m). The river bank has a strongly composite bank structure, with the undercutting taking place at the boundary between the gravel and soil layers in the river bank. At the sharp meander (NY 243 259), a further 58 m reach of actively-eroding river bank is found at the outside of the meander, with some block failures towards the downstream end of the section.

Figure 4.24: Bank 4 (West bank, NY 248 249, river flow left-right).

Figure 4.25: Bank 5 (West bank, NY 243 259, looking downstream).

The most extensive reach of active block failures occurred downstream of Low Stock Bridge, on the west bank of the River Derwent. This bank section includes over half (54%) of all actively eroding river bank lengths on the River Derwent between Derwent Water and Bassenthwaite Lake. A large proportion of the west bank of the river is actively eroding, and an area of spectacular block failures (Figures 4.26, 4.27) is found on the outside of the final meander before the lake inflow at Derwent Foot (bank 6). Three bank profiles were measured on the 235 m eroding reach, and were relatively low, between 0.9 m and 1.15 m in height. However, the bank was consistently steep throughout its length, and two profiles were undermined from the bank foot with overall gradients in excess of 90°. Maximum undercut depths were also considerable (240 mm, 280 mm, 450 mm). Several large, vegetated blocks of material were resting at the base of the river bank at Derwent Foot (Figures 4.27, 4.28). Most blocks were rectangular in shape and were up to 1 m in length. A large proportion of blocks were resting sub-parallel to the river bank line with their grassy top facing the channel, suggesting that they had rotated forwards during collapse. This suggests active beam failures (Section 2.4.2.1, Figure 2.15), which are likely to remain active as the upper bank remains undercut, with tension cracking present at the bank top in some areas of the bank.

Figure 4.26: Bank 6 (West bank, NY 232 272, looking downstream to Bassenthwaite Lake).

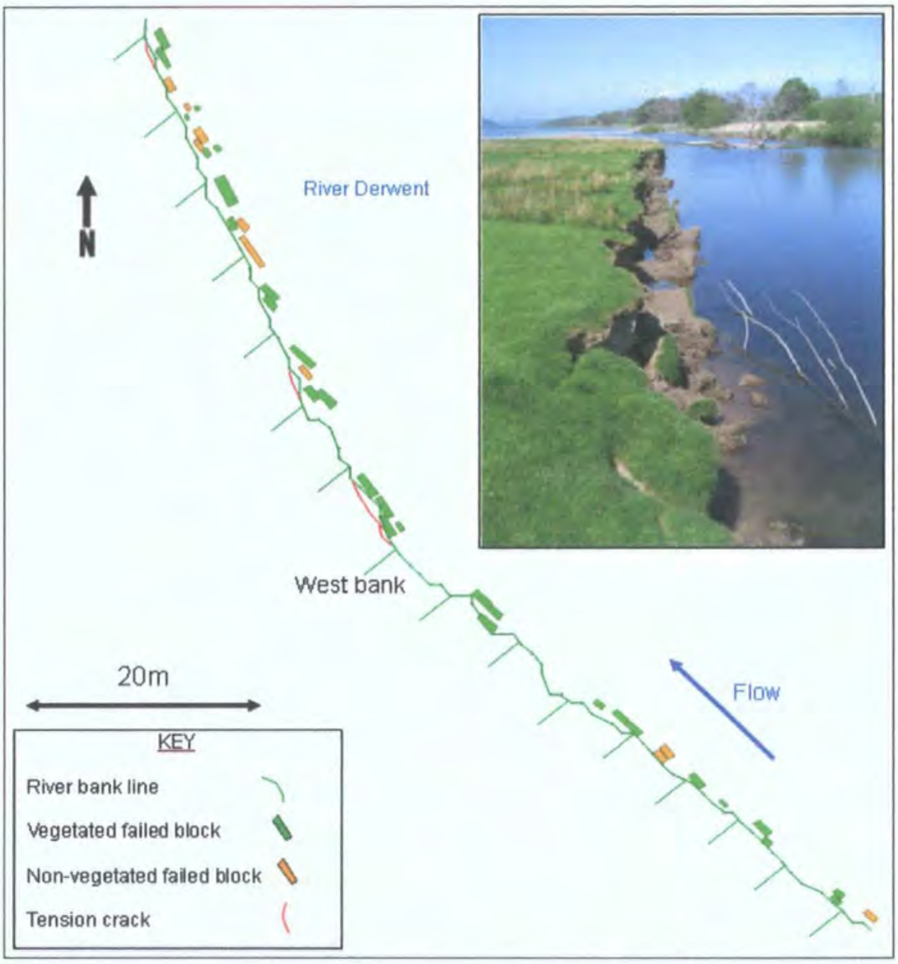

Figure 4.27: Map of the extensive block (cantilever) failures on the west bank of the River Derwent at Derwent Foot (bank 6), also showing photograph of the failures (looking downriver to Bassenthwaite Lake). Tension cracks at the bank top in the foreground suggest a very high likelihood of block failures following further erosion. Flow direction is away from photograph towards the lake.

It is known that, after failure, blocks of material can still retain their cohesion and can prove difficult to erode (Brunsden and Kesel 1973, Thorne and Tovey 1981). This is especially noticeable on the extensive section of block failures near the Bassenthwaite Lake inflow, as below the recently-eroded vegetated blocks there are several older unvegetated blocks that remain intact (Figures 4.27, 4.28).This suggests that despite the bank erosion, fine sediment supply to the channel did not occur when these blocks were detached. It is possible that the blocks could be eroded over longer periods of time by more powerful river flows, however it is unlikely that large volumes of sediment will be delivered from the blocks during moderate flow conditions.

Figure 4.28: Unvegetated, intact blocks (indicated by white arrows) lying in the river channel below more recent failures at bank 6 (flow direction: away from photograph).

Currently eroding river banks on the Derwent are therefore defined by a significantly higher gradient than non-eroding, stable river banks. Also, the depth of undercutting and the proportion of the river bank that is undermined appear to be significant factors in generating river bank instabilities. These observations mean that a significant proportion of eroded bank sections, which are steep and feature some undercutting, are at risk of bank failure and significant sediment supply to the channel in the event of erosion of the lower banks.

4.2.7 Morphology of semi-active river banks on the River Derwent

There are several river banks on the River Derwent which are clearly eroded, but do not appear to be actively eroding at present. They are defined as semi-active river banks (Section 4.2.6). Several such banks are located in areas where a line of trees grows at the bank top. Vegetation growth at the bank face is generally a strongly positive influence upon bank stability, with root growth improving bank cohesion and reducing the susceptibility of soil to erosion (Section 2.4.1). An excellent example of this is at a bank close to Portinscale at which was found to have a height of 3.5 m, with an undercut of 900 mm (Figure 4.29). Both these measurements are the largest of any river bank profile on the Derwent and suggest that the river bank should be unstable and actively eroding. However, the upper bank and undercut was composed of a dense vegetation layer which included several large tree roots, which appears to increase the cohesion of the upper river bank and provide support to the material. The lower bank had a relatively low gradient and no block failures, turf slippage or other evidence of erosion. Additionally, the river bank was composed of highly cohesive till, which appears to have considerable resistance to erosion. Similar bank sections were found between Portinscale and High Stock Bridge, with four banks found on the c. 350 m straight, tree-lined east bank downstream of the meander at NY 249 249. The four banks were in excess of 2.5 m in height, and three of the four profiles had maximum undercut depths of 300 mm or greater (with a maximum undercut depth of 760 mm). However, again the lower bank showed no sign of recent erosion, and several sections of these banks had remained stable long enough for grass and mosses to grow on some parts of the bank face. It is clear that vegetation had played a major role in influencing river bank form, as the trees on the bank tops had stabilized the upper river bank despite the presence of a large overhang. However, several trees on the bank tops in these areas have become significantly undermined (Figure 4.30), and when the tree eventually collapses into the river channel a large erosion event will take place, and the bank face will become much more susceptible to erosion (Figure 4.31). Some collapsed trees at the foot of the bank have been found in the wooded areas adjoining the east river bank of the Derwent between Portinscale and High Stock Bridge, and after the tree had collapsed, the bank face appeared steep and loose following the loss of cohesion (Figure 4.31). This is a major reason why single tree-lined channel banks were assessed as having a moderate-to-high sediment risk by Orr et al. (2004).

Figure 4.29: High (3.5 m) but presently stable river bank near Portinscale (NY 252 238), with metre ruler for scale. The dense vegetation roots at the overhang and the highly cohesive till on the lower, exposed bank face have prevented active erosion of this bank.

Figure 4.30: Semi-active exposed bank face between Portinscale and High Stock Bridge at NY 248 250, showing the influence of tree roots on river bank form and upper bank stability. The tree is however extremely undermined.

Figure 4.31: Collapsed bank-top tree at NY 247 251, showing a considerable amount of material removed from the bank attached to the roots, and a steep bank face left exposed by the removal of the material.

4.2.8 Poaching scars

Poaching scars were found in the field survey at several places along the river banks in areas where animals could access the bank face. The morphology of such scars was varied. The poaching scars could be distinguished into two broad categories of erosion. The first category of scars were found in places of controlled poaching at fenced areas of river bank (Figure 4.32). Several of these scars were found between High Stock Bridge and Low Stock Bridge, where the river banks are fenced and densely vegetated aside from fenced enclosures where grazing animals have been able to access the river banks for watering. Due to the high intensity of grazing at these areas, several of these scars are large, covering the whole of the river bank to water level. Good examples of these scars are found upstream of High Stock Bridge on the west bank at NY 244 257 and NY 243 258, and upstream of Low Stock Bridge (NY 244 257). It is notable that some scars had become grassed over, including a large hollow near Portinscale monitoring station (NY 252 238) suggesting that grazing pressure had been reduced at the location.

Figure 4.32: Large poaching scars: (left) near High Stock Bridge (NY 244 257), (right) near Low Stock Bridge (NY 244 257). Note the diversion of fencing into the river channel to allow grazing animals access to the water.

The second category of scars have formed as the result of uncontrolled access by grazing animals, on river banks which are unfenced and unprotected from grazing. Many scars have formed in areas of preferential grazing and animal movement, including near fences (Figure 4.33) and at areas of sheltered river banks (Figure 4.34). The formation of poaching scars by preferential grazing patterns is noted in the literature (Sheath 1998) and the scars that are formed are typically much smaller than the large scars described above, generally no more than 5 m across in any direction.

Figure 4.33: Examples of poaching scars formed near to fences in areas of channelled grazing: upstream of Low Stock Bridge (NY 237 264) (left) and near Portinscale (NY 253 237) (right).

Figure 4.34: Examples of poaching scars that have formed in sheltered areas of river bank: under trees near Portinscale (NY 251 240) (left), and below a steep bank face downstream of Low Stock Bridge (NY 236 268) (right).

Poaching scars make up just below 2% of the River Derwent's banks (Table 4.11), and although the transfer of sediment to the river from poaching scars has not been specifically studied during this project, several poaching scars comprise large areas of bare ground and loosened soil (Figure 4.35) as a result of frequent watering by grazing animals, and therefore constitute a potential fine sediment source. This is especially the case at the large scars in areas of controlled grazing at restricted access points, which are frequently grazed, providing fine sediment which could be entrained by surface run-off or river level rise. The former mechanism was observed at the large scar upstream of Low Stock Bridge in June 2007, following c. 30 minutes of heavy rain. During and after the rainfall, a cloud of suspended sediment formed in the river at the foot of the scar (Figure 4.11). It is likely that this mechanism takes place at other poaching scars, and due to the close proximity of the scar to the channel, fine sediment delivery is likely to be almost immediate. Therefore, poached river banks could deliver a significant volume of fine sediment to the channel if weather and river flow conditions are suitable.

Figure 4.35: Poaching scar at Low Stock Bridge (NY 236 268) showing hoofmarks and loosened soil at the lower part of the scar (indicated by arrow). Photograph looking downstream.

4.2.9 Bank weakening and preparation processes

Processes of bank weakening as a result of variations in temperature and moisture, particularly the effects of freeze-thaw weathering and needle ice (Section 2.4.4.1) and desiccation (Section 2.4.4.2) can increase the susceptibility of banks to erosion as well as deliver material to the channel by themselves. Although the processes have not been directly studied during this research project, observations suggest that they have been periodically active on the River Derwent. During the summer, several of the eroded bank sections took on a dried and desiccated appearance following a spell of warm and dry weather, with the upper river bank appearing crumbly and cracked (Figure 4.36). Although these processes may play an important role in preparing river banks for erosion, the overall volume of material delivered to the river channel by these processes would be very small in comparison to that transferred by larger erosion events.

Figure 4.36: Desiccated river bank face downstream of Low Stock Bridge at NY 235 269, showing the moisture contrast between the (dry) upper and lower bank.

4.2.10 River bank erosion detailed study

In order to assess changes in river bank morphology on a representative reach of the River Derwent, laser scanning of three eroded bank sections has taken place on the 13th March 2007 and 15th June 2007 (Section 3.3.2). In order to assess erosion rates and changes to bank morphology, the two scans at each river bank were compared using the program RealWorks Survey. Letters and numbers referred to in the text refer to labels on the three bank scan comparison diagrams, of bank 1 (Figure 4.37), bank 2 (Figure 4.38) and bank 3 (Figure 4.39).

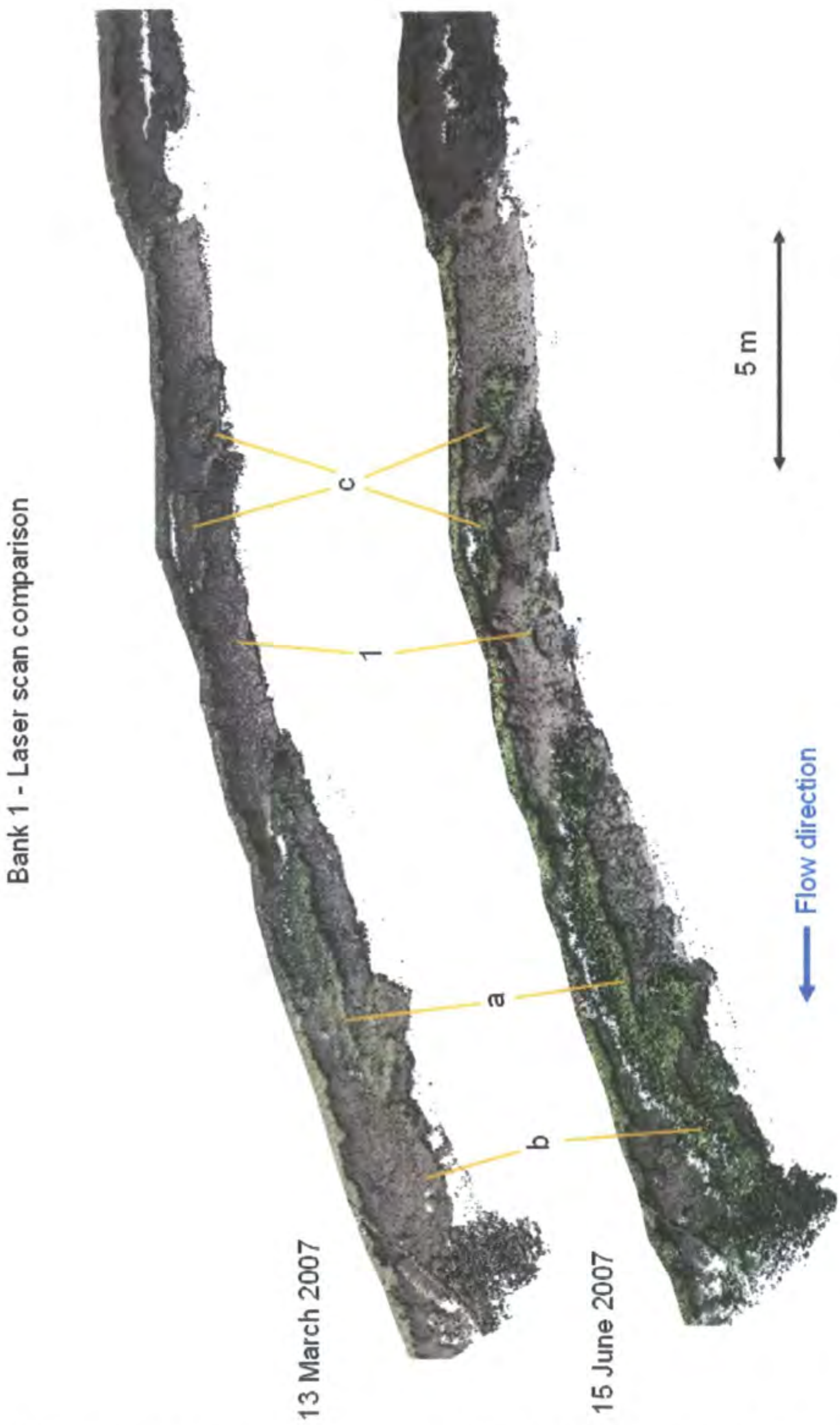

Figure 4.37: Bank 1 laser scan comparison. Labels on the diagram show areas of bank changes which are referred to in the text in Section 4.2.10.

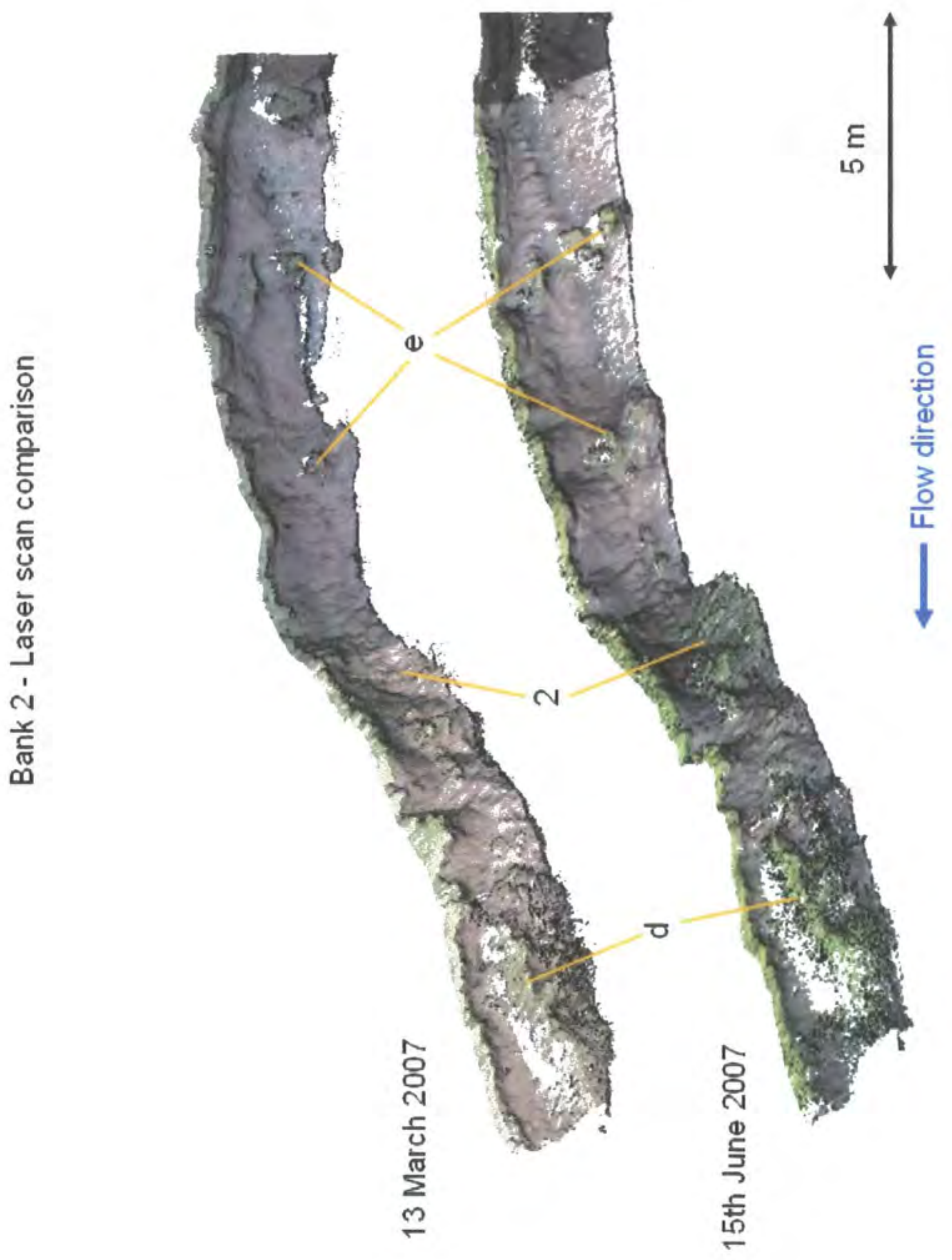

Figure 4.38: Bank 2 laser scan comparison.

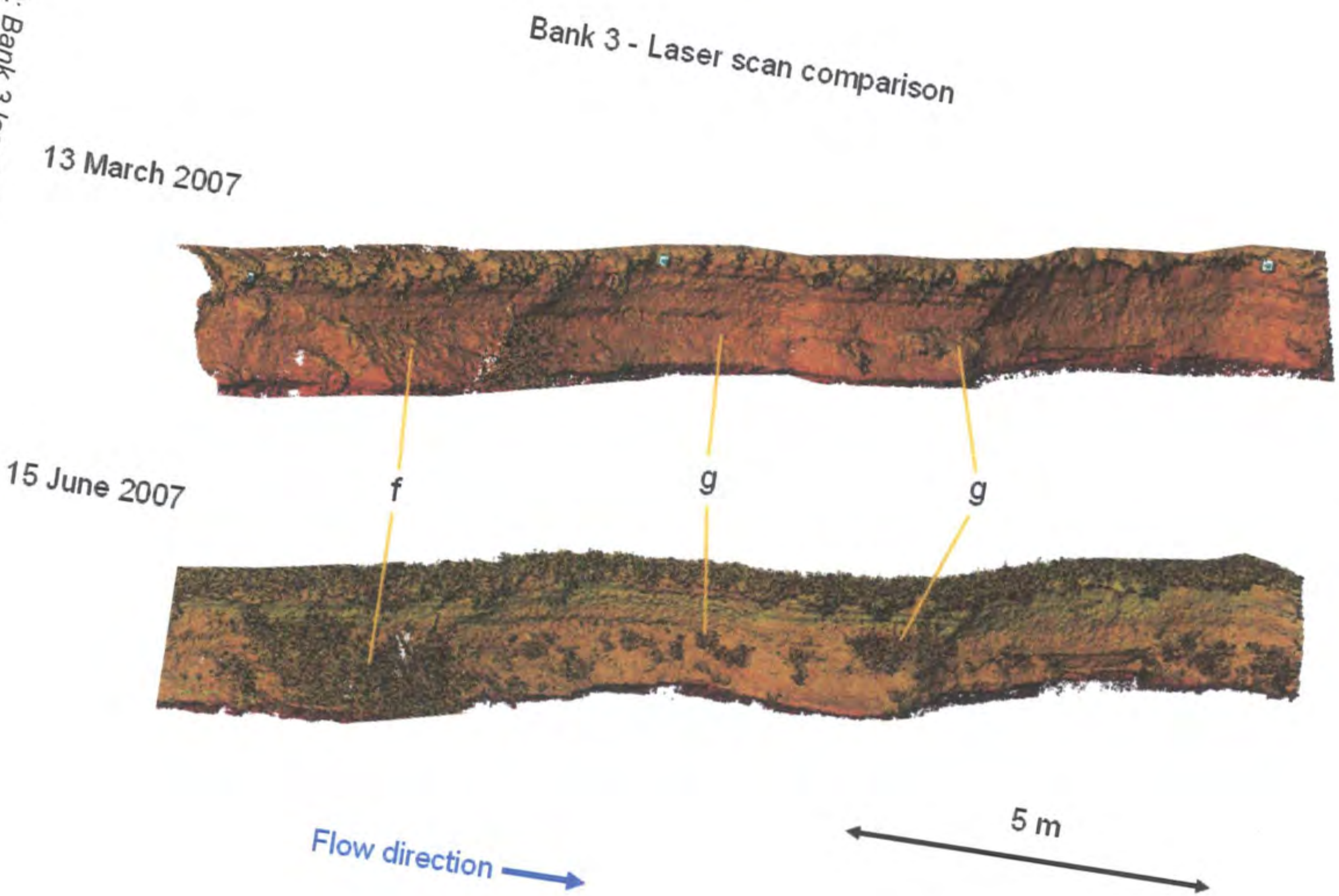

Figure 4.39: Bank 3 laser scan comparison.

The most notable change to occur at the river banks between the two scanning periods was an increase in vegetation cover. On bank 1 (Figure 4.37), the downstream c. 10 m of the bank became considerably more vegetated, in particular at the slumped shelf of material (a) and the formerly bare area of soil at the far downstream end of the reach (b). In the central area of bank 1, vegetation growth appears to have occurred on the tops of some failed blocks of material (c). Vegetation growth has clearly taken place at some parts of bank 2 (Figure 4.38), in particular a marked increase in vegetation density at the downstream end of the bank (d) and on the tops of some blocks of slumped material further upstream (e). At bank 3 (Figure 4.39), notable vegetation growth has occurred at the upstream end of the bank, particularly in a c. 3 m x 1.5 m section of bank face (f), as well as some clusters of vegetation growth at mid bank height along the previously bare river bank face (g). The increased erosion protection as a result of the vegetation growth (Section 2.4.1) means that stability in these areas is likely to be increased in the summer. The fact that the failed blocks and slumped areas became vegetated (c, e) suggests that the blocks do not constitute recent failures, as freshly failed blocks would typically lose vegetation fairly rapidly after becoming detached from the bank. It is likely that the blocks on banks 1 and 2 have remained in position for a longer period of time, and therefore vegetation has become established on their upper surface.

During the three month period between the scans, erosion rates on the river bank surfaces have been negligible. It is notable that the Low Stock Bridge turbidity record between the two laser scans (March-June 2007) suggests that sediment transfers on the River Derwent were small during this period, with no large spikes. This suggests an absence of river bank erosion and/or other sediment inputs. Some small changes to bank morphology have occurred, but they do not constitute major bank failures and are not likely to have supplied a large volume of sediment to the river channel. At bank 1 (Figure 4.37), a small failure scar on the lower bank appears on the 15th June scan which was not present on the 13th March scan (1). The small size of the feature (c. 0.75 m in length) makes it difficult to assess the feature, but its shape suggests a very small slip of material. On bank 2 (Figure 4.38), it appears that the mid-lower bank at a c. 4 m long reach in the central part of the bank is notably less steeper on the 15th June scan (2), possibly reflecting the erosion of the lower bank after river level rise, a process observed elsewhere on the River Derwent (Figures 4.22, 4.23). As there are several river banks on the River Derwent which are clearly in the process of active erosion (Section 4.2.6), the lack of active erosion on the three study banks is not an indication of the absence of erosion elsewhere.

The fact that the relatively small changes to river bank form (vegetation changes and limited erosion in some areas) have been identified by the laser scanner suggests that the technique is potentially useful in the study of river bank erosion. On river banks where erosion is more active, morphological changes to the river bank surface would be shown clearly by comparisons of the scans. It is clear a study of some of the actively eroding bank sections downstream of Low

Stock Bridge may have yielded significant changes to river bank morphology over the short (3 month) timescale of study. It is clear that a longer study period would be necessary to survey bank erosion rates at the three banks observed during this project, due to the lack of active erosion.

4.2.11 Methods of river bank management

This section summarises attempts to manage the banks of the River Derwent. The presence of river bank management schemes limit the potential extent of bank erosion, and it is clear that some schemes have been installed to prevent future erosion. The two principal modern management techniques have been to encourage vegetation growth by stock exclusion or tree planting (Section 4.2.11.1) and the use of large stone revetments and reinforced levees (Section 4.2.11.2). The implications of these management techniques are described below.

4.2.11.1 Vegetation plantation

The addition of vegetation to river banks is known to have a positive influence on overall bank stability (Section 2.4.1). Vegetation growth has been encouraged on some bank reaches on the River Derwent by the fencing off of adjacent grazing land from the bank face. The recent AXIS Consultancy Report (2007) has identified the planting and encouragement of vegetation growth in 'buffer zones' as a key method of reducing fine sediment delivery from the floodplain in the Bassenthwaite Lake catchment, a recommendation made by other studies of the area (e.g. Nisbet et al. 2004, Orr et al. 2004). In order to encourage vegetation growth and prevent river bank poaching by grazing animals, fencing has been installed on the bank top of the Derwent's channel between High Stock Bridge (NY 243 259) and Low Stock Bridge (NY 236 268). On this reach, the entire west bank has been fenced, with a c. 500m section of the east bank to the north of High Stock Bridge. The river banks between the channel and the bank top fence are covered by high density vegetation, including grasses, shrubs and bushes, with some areas of recently-planted trees between the fence and the channel (Figure 4.41). This vegetation is likely to increase the stability of the river bank in this area and contribute to erosion protection. Similarly, the east river bank downstream of Low Stock Bridge is not grazed and features dense vegetation at the bank top and bank face (Figure 4.41), as well as some areas of reeds and grasses at the bank foot near the lake. The latter vegetation also reduces flow velocities at the bank foot and trap sediment (Section 2.4.1) and the river bank in this area has a very low height and gradient. Very little river bank erosion is found on this reach, in contrast to the extensive active bank erosion occurring on the west bank downstream of Low Stock Bridge, which is grazed, unprotected and has little vegetation except for the short grass at the bank top (Figure 4.40). The fact that grazing animals can access the river bank face has also led to several small poaching scars developing on the west river bank (e.g. Figure 4.35).

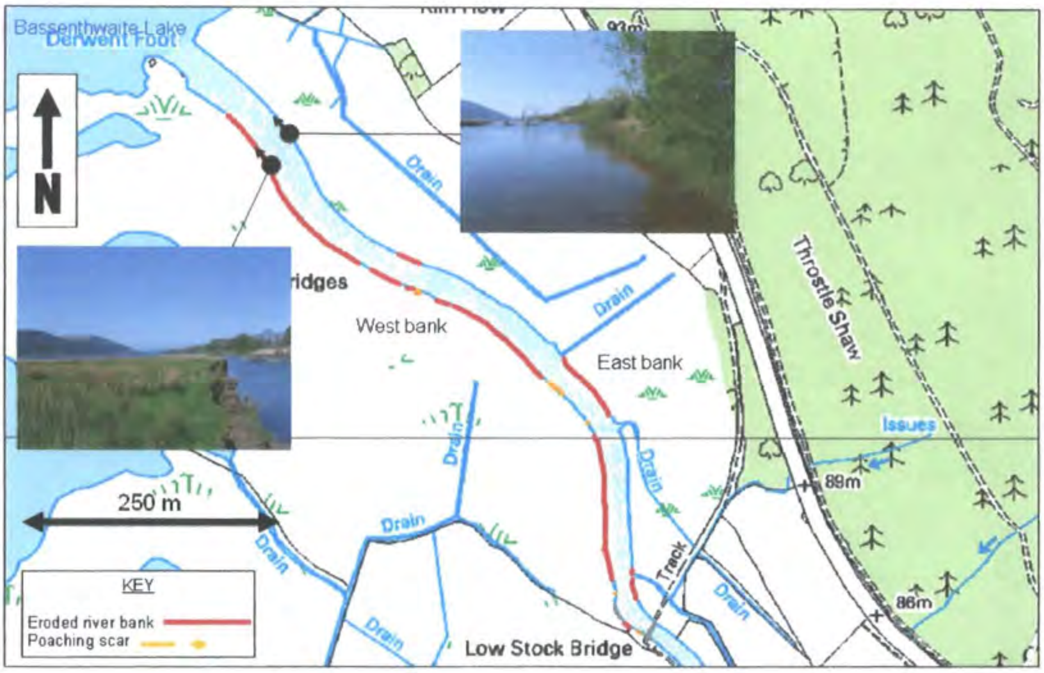

Figure 4.40: Contrast between erosion extent on the west and east banks of the River Derwent between Low Stock Bridge and Bassenthwaite Lake. Photographs show representative river bank vegetation cover on each river bank.

Figure 4.41: Field management techniques on the River Derwent (all photographs looking downstream). Top right: dense vegetation on a fenced bank downstream of High Stock Bridge (NY 243 260). Top left: Tree plantation and bank top fence installation upstream of Low Stock Bridge (NY 236 267). Bottom: Willow bank spiling installed on a c. 40 m reach of riverbank upstream of Low Stock Bridge (NY 236 266), showing (left) newly planted spiling in March 2007 and (right) willow growth by June 2007.

There is evidence that the plantation of vegetation has taken place on some areas of river bank in order to increase river bank protection from erosion.

These include some small plantations of young trees on the west bank upstream of Low Stock Bridge (Figure 4.41). Additionally, willow spiling has been installed on a c. 20 m section of the west bank of the Derwent upstream of Low Stock Bridge at NY 237 266. The willow was planted during March 2007, and by the spring the vegetation cover on the bank had increased considerably (Figure 4.41). An older area of spiling is situated upstream of Portinscale on the west bank between NY 255 238 and NY 256 237. The increased root density and increased vegetation cover will increase bank protection from erosion, reducing the risk of bank failure and sediment delivery in these areas.

4.2.11.2 Revetments

Revetments are commonly used to straighten the river channel, act as flood defences and to protect river banks. Compared with other rivers in the Bassenthwaite catchment (in particular the River Greta and Newlands Beck), the River Derwent's channel between Derwent Water and Bassenthwaite Lake has not been extensively modified (Section 2.1.2). During this field survey, the overall length of stone revetments on the Derwent was measured at 760 m, or 5.4% of the total length of the river channel. There are however large areas of engineered river banks near Portinscale. The largest revetment of this type is a 170 m long raised embankment situated on the east bank of the Derwent between the A66 road bridge (NY 251 241) and the environs of the old railway bridge (NY 249 241) (Figure 4.42). This bank is in the form of a mound of boulders (maximum height c. 4 m) at the channel edge. Furthermore, an 85 m stone revetment is found opposite Portinscale gauging station to the north of NY 251 238 (Figure 4.43), with similar revetments on the east bank near the gauging station. These revetments are placed to stabilise the weir at the gauging station. Aside from these large revetments and some shorter sections close to Portinscale, including the banks at the recreational area close to Portinscale suspension footbridge (NY 253 237), the largely agricultural reaches to the north of Portinscale do not feature extensive stone revetments. Some sections of boulders are found near Low Stock Bridge, including a 40 m section to the north of a reinforced promontory at NY 236 265. Gabions, constructed as five walls built perpendicular to the bank line (maximum height c. 2-3 m) were found on the east bank of the Derwent at NY 247 251 (Figure 4.44). Such features are not widespread on the River Derwent, but prevent erosion in areas where they do exist.

Figure 4.42: Large stone revetment in the form of a raised embankment on the east bank of the River Derwent to the north of the A66 bridge (NY 250 241, looking downstream).

Figure 4.43: Boulder revetment wall at Portinscale (NY 251 238, looking upstream).

Figure 4.44: Gabion cages between Portinscale and High Stock Bridge (NY 247 251, looking upstream).

4.2.12 Summary and conclusions

The extent of bank erosion on the River Derwent is clearly considerable, with over a fifth of the River Derwent's banks eroded, just over 40% of which comprises presently active river bank failures (Section 4.2.2, Table 4.11). A large proportion of river bank erosion, in particular active bank failures, is found in areas of large historical channel migration (Section 4.2.3). Bank erosion has been restricted in areas of river bank management (Section 4.2.11), although such areas only cover a small proportion of the River Derwent's channel.

As discussed in Chapter 2, river bank failures become more likely with increasing gradient and undercutting (Section 2.4.1), and therefore fine sediment delivery risks on the River Derwent are considerable, as a large number of eroded river bank sections are both steep and undercut (Section 4.2.5), and such banks therefore have potential to fail in the future, particularly following the actions of erosive high river discharges which could convert presently semi-active river banks into actively eroding banks. It is difficult to assess thresholds at which river bank sections that are presently stable will fail, however, material removal from the bank foot area during high river flows, leading to increased bank steepness and undercutting, will increase the likelihood of large bank failures, including block failures. This mechanism has been observed in the field at the actively eroding bank near Portinscale Bridge (Section 4.2.6.2, Figures 4.22, 4.23). Furthermore, the river bank sections currently undergoing active erosion and block failures at present have considerably steeper gradients than stable banks. Many of these block failures occur as a result of a favourable bank composition, with undermining of the upper bank facilitated by composite bank structures and non-cohesive material situated at a low elevation on the bank (Section 4.2.4). A large proportion of all actively eroding banks are found on the west bank of the Derwent downstream of Low Stock Bridge (Section 4.2.6.2). It does not appear that height is, of itself, a contributing factor to river bank instability, as many of the highest banks on the river are presently stable, mostly due to the influence of vegetation (Section 4.2.7).

Other processes of bank erosion are of varying significance to overall fine sediment supply. While bank weakening and preparation processes are only likely to supply a very small volume of sediment to the channel (Section 4.2.9), the erosion of poaching scars may supply a larger volume of sediment in the event of surface run-off or river level rise (Section 4.2.8), as suggested by field observations of this mechanism.

The survey of river bank morphological changes carried out using laser scan comparisons suggests minimal changes to river bank form at three eroded banks upstream of Low Stock Bridge (Section 4.2.10). As active bank failures have been observed on other reaches of the Derwent (Section 4.2.6), it is possible that the river banks that were chosen to form the study area are not in the process of active erosion, particularly over a relatively short (three month) study period. However, it is apparent that the use of the terrestrial laser scanner to assess river bank erosion is a useful method, as the high resolution of the scans enabled clear and detailed comparisons to be made of bank morphological changes.

To answer the initial research question, it is highly likely that river bank erosion is an important source of fine sediment on the River Derwent, and therefore an important source of suspended sediment to the catchment sediment budget and Bassenthwaite Lake. This is suggested by the large extent of river bank erosion and evidence of active bank failures on several reaches of the Derwent, and the potentially unstable morphology of several presently semi-active river banks. As a large increase in sediment load has been shown to occur on the lowland River Derwent (Section 4.1.3.2), it is very possible that river bank erosion events provide a sizeable proportion of the overall fine sediment input in this region.

CHAPTER FIVE

CONCLUSIONS

This chapter provides a summary of the key findings of this research and presents a summary sediment budget for fine sediment fluxes in the Bassenthwaite Lake catchment. It is known that Bassenthwaite Lake has suffered a deterioration of water quality, potentially as a result of increased fine sediment transfers to the lake, which has caused a decline in the population of the rare vendace (*Coregonus albula*) (Chapter 1). The project aim was to describe the characteristics of fluvial suspended sediment transfers to Bassenthwaite Lake through direct monitoring of the River Derwent and Newlands Beck (at the head of Bassenthwaite Lake) in order to assess the potential contribution of river bank erosion on the lowland River Derwent to fine sediment delivery.

5.1 Research question 1: What are the characteristics of suspended sediment transfers to Bassenthwaite Lake?

- Suspended sediment transfers in the lowland Bassenthwaite Lake catchment typically occur during infrequent, high-magnitude flow events which are responsible for the transfer of a large proportion of the overall fine sediment load. Approximately two-thirds of the total suspended sediment transfers on the River Derwent occurred during just over 10% of the time (Figure 4.5).

- The River Derwent supplies the largest suspended sediment input to Bassenthwaite Lake. The river had an overall sediment load five times larger than that of Newlands Beck (Figure 4.6). This is also demonstrated in the river water sample record, which suggests that the mean suspended sediment concentration on the Derwent was 56% higher than Newlands Beck (Section 4.1.3.1).
- Fine sediment is supplied to the river along the lowland Derwent, between Portinscale and Low Stock Bridge, as demonstrated by an increase in total suspended sediment loads (estimated at 1,158 t a^{-1}) between the two monitoring stations (Figure 5.1). Fine sediment transfer in this reach results from a combination of sediment inputs from the wider catchment, and brief pulses of suspended sediment added by active erosion (river bank failures) on the lowland River Derwent.
- The overall sediment load calculations from turbidity monitoring and the accompanying water sampling suggest that a large volume of fine sediment (4,469 t a^{-1}) is stored in Bassenthwaite Lake (Figure 5.1). This equates to an average sedimentation rate of 0.08 g cm a^{-1}, which is comparable with the rate of c. 0.1 g cm a^{-1} approximated from sediment core records (Cranwell et al. 1995, Bennion et al. 2000).

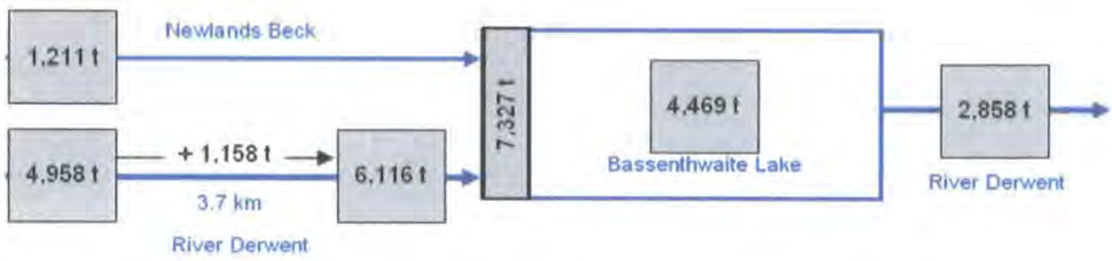

Figure 5.1: Summary of the estimated annual sediment budget for the Bassenthwaite lowland catchment. Inflows to the lake show suspended sediment loads extrapolated from the 8-month turbidity monitoring period (Section 4.1.3.2). Sediment storage in Bassenthwaite Lake and sediment outflows from the lake were estimated from the suspended sediment concentration records (Section 4.1.3.1).

5.2 Research question 2: To what extent does river bank erosion constitute an important fine sediment source on the lowland River Derwent?

- Field evidence of extensive bank erosion on the River Derwent,suggests that river bank erosion constitutes a major fine sediment source on the lower Derwent, and therefore an important sediment input to Bassenthwaite Lake.
- Over 21% of river banks on the River Derwent between Derwent Water and Bassenthwaite Lake are eroded, of which approximately 40% are actively eroding.
- A high proportion of eroded river banks are susceptible to large-scale bank failures. Failed blocks have been observed at several river banks, and the dominant erosion mechanism on the river appears to be lower bank erosion and undercutting by high river discharges, leading to cantilever failure.

- Livestock poaching scars are likely to be sources of fine sediment to the channel during rainfall and periods of high river levels. Based on field observations, river bank weakening processes, including freeze-thaw and desiccation, are thought to be insignificant in overall sediment delivery.

5.3 Recommendations for further study

Further monitoring of suspended sediment transfers within the Bassenthwaite Lake area is necessary in order to gain a fuller understanding of patterns of suspended sediment transfers to Bassenthwaite Lake. Although the water sample record analysed in this project covers a period of just under two and a half years, the nature of water sampling means that large periods of river flows were not directly sampled. The continuous turbidity monitoring has proved most useful in the analysis of overall sediment loads and suspended sediment dynamics during high flow events, however this comprises only eight months of monitoring of sediment inputs to Bassenthwaite. A more sustained water sampling programme, together with continuous turbidity monitoring, is necessary in order to further quantify suspended sediment transfers, particularly on the River Derwent. There is also uncertainty as to the outflow sediment load from Bassenthwaite Lake, and therefore the volume of sediment being trapped in the lake, as the loads shown in Figure 5.1 are only preliminary estimates. Monitoring of suspended sediment transfers is fundamental in assessing the impact of any remediation work aimed at reducing sediment supply in the catchment.

Future monitoring of river bank erosion is also important, as this project has concluded that the extensive eroded banks of the River Derwent are an important source of fine sediment to Bassenthwaite Lake. In particular, monitoring of the length of active river bank erosion and bank failures (the areas of river bank that are presently transferring sediment to the river channel) will enable the risk of fine sediment delivery to be assessed in future years. Repeated laser scans of the river banks near Low Stock Bridge, in comparison with the scan data collected during 2007, are planned and will also contribute to this process.

The preliminary sediment budget described in Section 4.1 and shown in Figure 5.1 is the first detailed attempt at a sediment budget for Bassenthwaite Lake. This clearly demonstrates the importance of the river inputs and the trapping efficiency of the lake. Intriguingly, based on this first approximation, the calculated sedimentation rate agrees closely with estimates measured from lake cores. However, this value can be expected to be higher if sediment focussing is considered, autochthonous sedimentation included, and inputs from unmeasured streams calculated.

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