Spatial patterns of fine sediment supply and transfer in the River Esk, North York Moors.

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MSc (by Research)

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Declaration

This thesis is the result of my own work. Data from other authors which are referred to in the thesis are acknowledged at the appropriate point in the text.

Statement of Copyright

Abstract

A detailed field study of spatial and temporal patterns of fine sediment transfer was undertaken in the River Esk catchment, North York Moors in response to ecological problems associated with in-channel fine sedimentation. Fine sediment flux and specific sediment yields were estimated from bulk suspended sediment samples collected from a network of 17 spatially distributed Time Integrated Samplers (TIMS). These samplers were deployed over a six month monitoring period from December 2005 – June 2006. Channel characteristics (bank height; bank material; vegetation cover / type; and erosion extent / type); catchment properties (e.g. drains, tributaries and areas of saturated runoff); and land use were mapped using a stream reconnaissance survey covering 61 km of the River Esk and dominant tributaries. These mapped attributes were combined in ArcGIS with other spatial data (e.g. geology; land elevation and slope) to create a GIS database. Dominant sediment source areas were identified by comparing sediment characteristics (e.g. colour; magnetic susceptibility; and metal concentrations) of the suspended material retained in the TIMS samplers with those of channel bank and catchment source samples.

Two main areas of high fine sediment flux were identified on the Esk between: Danby to Duck Bridge; and Egton Bridge to Grosmont. Fine sediment in the Danby to Duck Bridge reach was sourced predominantly from local channel banks as a result of geotechnical failures. However from Egton Bridge to Grosmont, catchment sediment sources, from the steep, forested, boulder clay sub-catchments of the dominant tributaries (Glaisdale Beck and Butter Beck), were most significant. To alleviate high level of sedimentation in these locations, the main areas requiring management are the channel banks of the Esk near Danby; intensively farm areas of Danby Beck and Great Fryup Beck; and the steep, wooded regions in Glaisdale Beck and Butter Beck sub-catchments. Suitable target initiatives should include: riparian fencing; bank reinforcements; livestock rotation; and the creation of buffer zones.

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Chapter One: INTRODUCTION

1.1 Research rationale

Changes in traditional land use management practices in Upland Britain have occurred in recent years in response to increasing population demands. These include shifts from spring to autumn sown cereals; increased livestock numbers; increased occurrence of moorland fires for grouse shooting; and increased density of roads, paths, tracks and field drains. This is as a result of intensification of farming practices, increased forestry plantations and increased tourism in rural Britain (Heatherwaite *et al.*, 1990). Such land use changes enhance soil disturbance, decrease the vegetation cover and increase the compaction of the soil (Collins and Walling, 2004); hence increase the potential to mobilise large quantities of weakly cohesive surface material. This decreases the infiltration rate of the soil and enhances runoff, detachment and transfer of fine sediment to the river system (Marks and Graham, 1997).

High rates of fine sediment delivery to Upland river systems can cause management problems, notably where they result in increased rates of sedimentation and detrimental impacts to in-stream habitats (Walling, 2005). For example, increased rates of fine sediment mobilisation and transport are not only major sources of contaminant transfer, as fine sediment acts as a carrier and storage agent of other pollutants such as pesticides and herbicides (Xiaoqing, 2003); but can also cause serious problems to aquatic environments. These include: clogging the gills of aquatic organisms; interfering with feeding for visual feeders; destroying the habitat for bottom dwelling organisms; and decreasing the amount of light penetration, therefore reducing the primary productivity of the whole fluvial ecosystem (Wood and Armitage, 1997). Figure 1.1 summarises the link between changes in land use management practices in Upland areas and increased fine sediment inputs, transport and deposition in the drainage basin; and subsequent detrimental impacts on in-stream habitats.

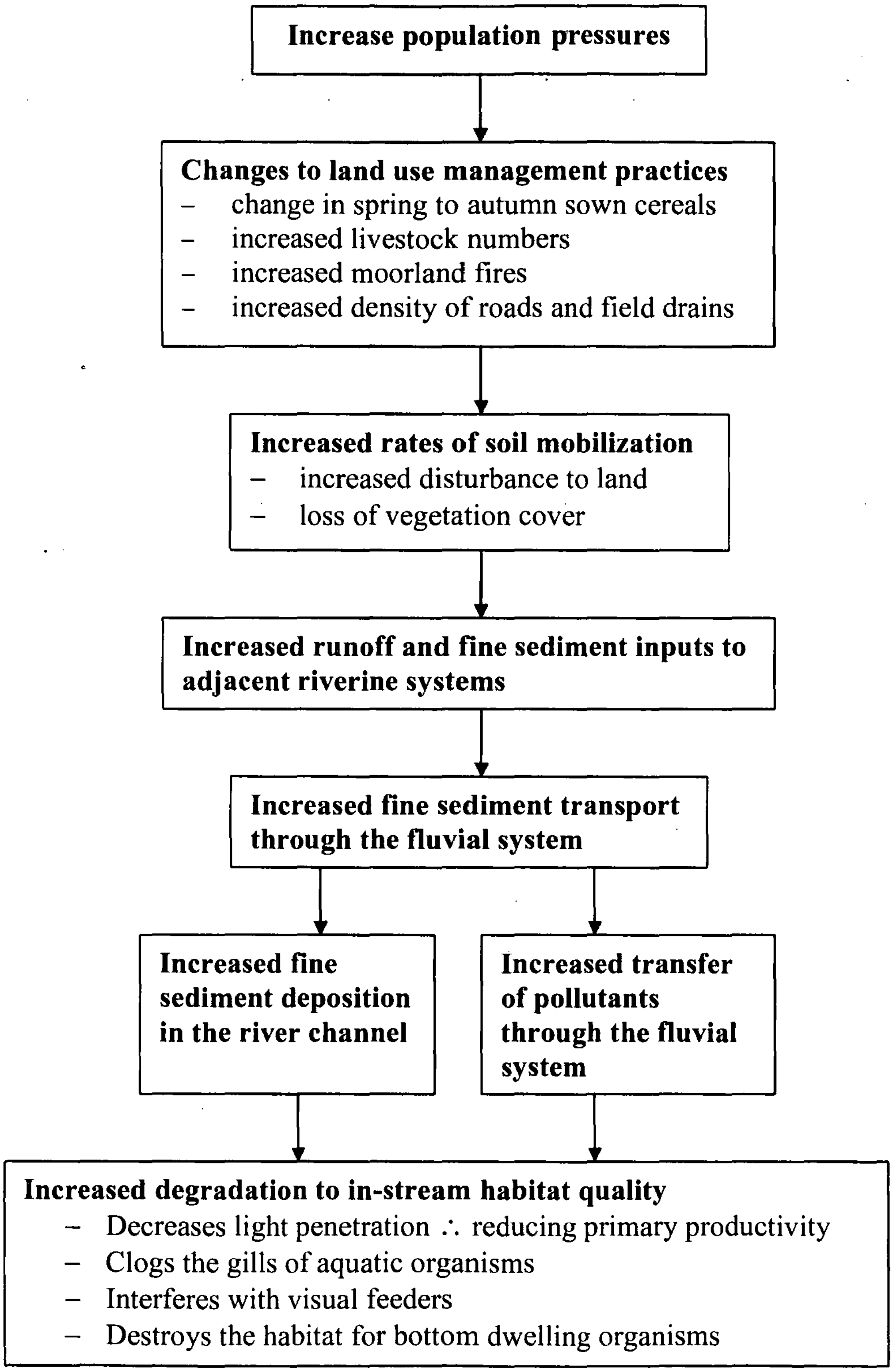


Figure 1.1: Flowchart illustrating the links between land use, fine sediment and in-stream habitats

Projected increases in precipitation and storm events associated with climate change and increased intensity of land use and management practices could significantly enhance these problems in the future if they result in increased sediment delivery to the river network (Walling *et al.*, 1999a). Hence an improved understanding of suspended sediment transfers and the provision of detailed information on both the nature and relative contributions of the dominant sediment sources within a catchment are an essential requirements for assisting the design and implementation of targeted management strategies for controlling and reducing sediment mobilization (Collins and Walling, 2004).

In the UK recent concern for the improvement of river water quality and the ecological status of aquatic habitats, prompted by the EC Water Framework and Habitats Directives, has now identified fine sediment as a key contributor to diffuse and point source pollution and the consequent degradation of aquatic habitats (Walling, 2004). This has emphasised the need to control sediment transfers and delivery to water courses in the UK, even though rates of soil loss and specific suspended sediment yields are low by world standards. Moreover, the Upland catchments in the UK are thought to be particularly sensitive to changes in land use management practices (Evans and Burt, 1998). However at present, there is an inadequacy of both existing knowledge and current monitoring programmes characterising fine sediment dynamics, and their processes in Upland catchments (Collins *et al.*, 1997a).

The River Esk catchment in the UK is representative of a small, predominantly rural Upland case study, where recent changes to land use management practices (e.g. intensification of stocking numbers; increased occurrence of moorland fires; and reafforestation) are thought to have altered patterns of suspended sediment dynamics in recent years (EA, 2004). As a result, elevated levels of sedimentation in the River Esk has been attributed to the recent decline of salmonid and pearl mussel aquatic habitats (EA, 2005); highlighting the need to implement catchment management initiatives aimed at alleviating fine sediment inputs and transfers. Thus, the River Esk provides an interesting and relevant catchment study in which to investigate spatial and temporal patterns of fine sediment flux.

1.2 Research aims and objectives

The aim of this research is to assess the relationship between spatial variations in fine sediment supply and their dominant source areas in the River Esk catchment, North York Moors. This can then inform effective management strategies to reduce sedimentation in the Esk catchment.

This aim can be broken down into five main research objectives:

1) to determine spatial variations in fine sediment transfer, identifying dominant reaches with high suspended sediment flux in the River Esk catchment;

Spatial patterns of fine sediment transfer can be analysed in detail by identifying the main zones of sediment mobilisation and deposition, establishing dominant 'hotspots' of fine sediment flux in the catchment. This can then be used to offer a preliminary insight to the importance of certain tributaries and sections of the main Esk in supplying fine sediment to the Esk catchment.

2) to determine the temporal influence of flow dynamics on spatial patterns of sediment transfer;

Given that 90% of the fine material in a catchment basin is moved during high flow conditions (Walling, 1990), consideration of the influence of variable flow dynamics on these spatial patterns of fine sediment is essential; without which, any inferred conclusions on spatial patterns of fine sediment could be in error.

3) to understand the links between spatial patterns of fine sediment flux with both channel and catchment scale characteristics, using channel mapping techniques to create a GIS database of catchment attributes;

To understand the spatial patterns in fine sediment flux within the catchment and to inform effective integrated management strategies, it is necessary to understand the processes and changes that occur between the source areas and areas of suspended sediment deposition further downstream. This can be done by mapping attributes at both channel (e.g. bank material, bank height and extent of erosion) and catchment scales (e.g. land use; geology and topography). Using GIS software allows large amounts of spatial data, at varying spatial scales, to be easily assimilated and combined.

4) to identify the main sediment source areas in the catchment that supply the dominant zones of high suspended sediment flux;

In order to link these problem areas of high suspended sediment supply and sedimentation to specific land use management practices, it is necessary to establish the origin of the dominant sources of fine sediment within the catchment. However as yet the principal sources of the suspended sediment fluxes from many river basins have not been well documented and establishing catchment suspended sediment sources is fraught with difficulty (Collins and Walling, 2004). Therefore, in attaining this research objective, this research will not only identify dominant sediment source areas in the Esk, but also add to the knowledge base of documenting and understanding fine sediment transfers in UK Upland catchments.

5) to inform effective management strategies to alleviate sedimentation in problem areas.

It is necessary to link established spatial and temporal patterns of sediment transfers to particular land use practices in the Esk catchment so to infer which activities, if any, have caused an increase in the rate of sedimentation. This can be done by combining the data collected from Research objectives 1 - 4 to produce a sediment budget indicating the dominant locations of fine sediment transfers, storages, sources, and important transfer mechanisms. This can then be used to inform the development of effective targeted management strategies in the Esk catchment.

A simple conceptual framework that forms the basis to this research project is illustrated in Figure 1.2.

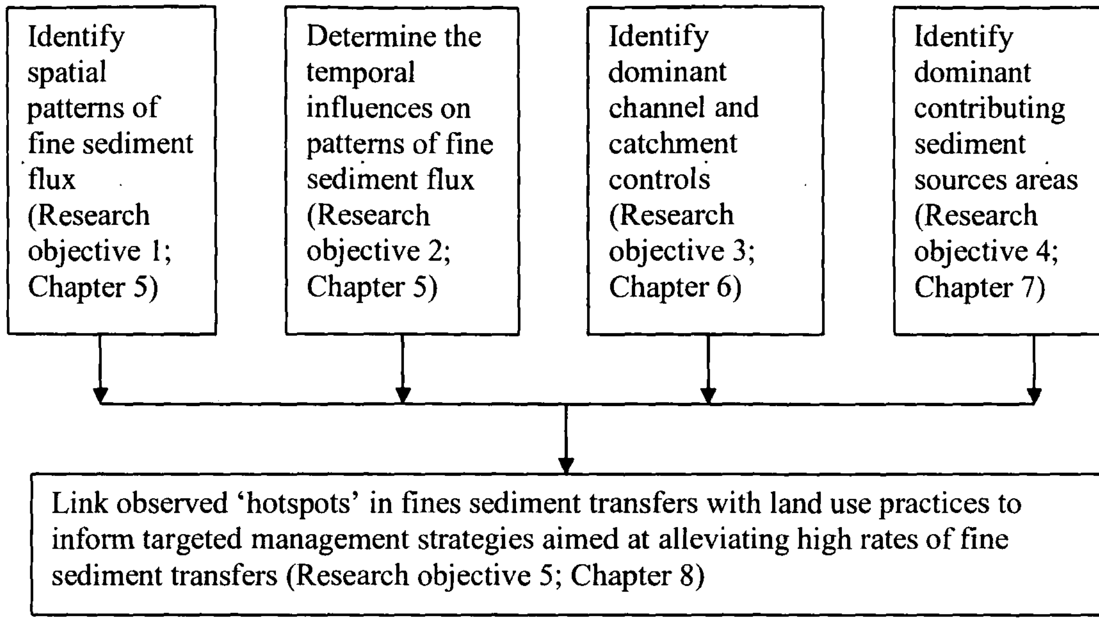


Figure 1.2: Basic conceptual framework of this research project

1.3 Thesis structure

Chapter 2 provides more detail explaining the background and spatial controls on fine sediment dynamics, how land use management practices affect spatial patterns, and the subsequent affect on aquatic habitats. Chapter 2 also provides a review on existing studies of spatial patterns of fine sediment in the British Uplands and a critique of current methods of monitoring and characterising fine sediment flux.

This is followed by Chapter 3, which details the study area and Chapter 4, which provides a summary of the main research methods used. The next three chapters discuss the substantive results; Chapter 5 examines the spatial and temporal variation of fine sediment flux in the Esk catchment; Chapter 6 summarises the channel mapping and catchment characteristics and; Chapter 7 details the results of the sediment source identification investigations.

Chapter 8 provides a synthesis and discussion of the results by creating a schematic sediment budget for the Esk catchment. This is then assessed in relation to the locations of the critical species habitats in the catchment (spawning salmonids and freshwater pearl mussels) to create an integrated catchment management strategy for alleviating high rates of fine sedimentation. Chapter 8 also provides a discussion of the applications and importance of this research to other investigations. Finally, the conclusions, limitations and further research are presented in Chapter 9.

Chapter Two: BACKGROUND TO FINE SEDIMENT FLUX IN FLUVIAL SYSTEMS

2.1 Overview

This chapter firstly defines and considers the fundamental principles of fine sediment transfer in the fluvial systems. Both small and large scale catchment variables governing spatial patterns of sediment flux, at ranging spatial and temporal scales, are also examined. A review is then given of existing investigations of suspended sediment dynamics within the British Upland setting. Following on from this, evidence suggesting the link between intensive land use management practices, high sediment inputs and its subsequent detrimental effects on the aquatic environment in Upland catchments are examined. This subsequently highlights the need for management and in accordance, a brief overview of possible management strategies in alleviating high levels of fine sediment transfers is given. This draws attention to a lack of adequate records on suspended sediment characteristics and its dominant source areas; essential for informing effective management decisions in the UK. Hence, existing studies monitoring and recording spatial patterns of fine sediment flux and associated catchment characteristics in the British Uplands are evaluated. The potential of 'fingerprinting' dominant sediment sources areas within a catchment is also discussed.

2.2 Fine sediment definitions

Sediment transport can be loosely defined as the mass (m^3) of sediment moving over a width of the bed (m) over a unit of time (s) (Bridge, 2003). In more detail, Graf (1998) describes sediment transport by sub-dividing it into 3 main types; bed load transport; suspended load and wash load (Table 2.1). The main sediment transport processes for which are illustrated in Figure 2.1:

Table 2.1: Types of sediment transport in river systems (Source: Graf, 1998)

Sediment Transport	Description
Bed load transport	Consists of larger particles that remain in close contact with the bed and move downstream by saltation and traction (by bouncing, sliding and rolling on or over the stream bed by the force of water).
Suspended load	Consists of material transported in solution under the influence of turbulence. Suspended sediment is occasionally in contact with the bed and moves by large jumps in the water column.
Wash load	Finest particles rarely in contact with the bed and are readily moved.

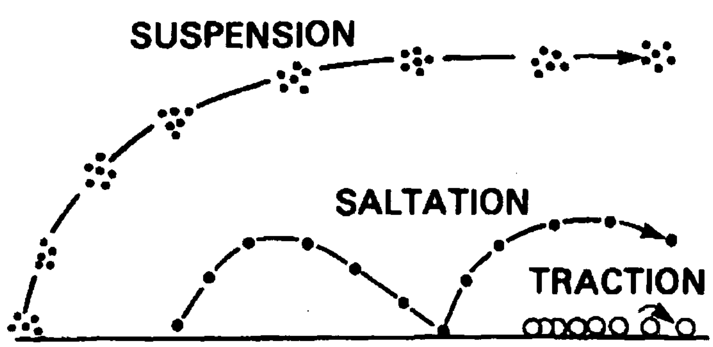


Figure 2.1: The major sediment transport processes (Source: Newson, 1997)

However, these transport phases are much debated within fluvial literature; Xiaoquing (2003) classifies sediment transported in rivers as either bed material load or wash load. Wash load consists of fine particles, usually sediment finer than 63 μm, which have been eroded and washed from Upland watersheds and transported long distances. The amount of wash load transported in a river depends upon the supply from the source areas. Bed load material, on the other hand, is coarser, directly supplied from the channel bed and is controlled by the transport capacity of the stream. The amount of bed load material depends on the composition of the bed and relevant hydraulic parameters. It can move as either temporary suspended sediment load or as bed load (Xiaguing, 2003).

However it is the transport of fine sediment, defined as particles less than 63 μm (Wood and Armitage, 1997), that is commonly the dominant form of sediment transport from land to rivers and is the important fraction in terms of aquatic pollution and contaminant adsorption. This is due to their relatively large surface areas and geochemical composition. Thus, it is the transport of fine sediment, which includes both the wash load and suspended sediment load that forms the primary focus of this research.

A number of terms regarding fine sediment transport are referred to throughout this thesis and the definitions used for each are outlined below:

- **Suspended sediment:** the sediment that is maintained in suspension by the upward components of turbulent currents.
- **Suspended sediment concentration (SSC):** the ratio of the mass of dry sediment in a water-sediment mixture to the mass of the water-sediment mixture.
- **Sediment flux:** the total amount of suspended sediment transported through a cross section, measurable at a point of reference and for a specified period of time, expressed in absolute terms (g d^{-1}).
- **Sediment yield:** the total sediment outflow from a catchment, measurable at a point of reference and for a specified period of time, expressed in area specific terms (g km^{-1} d^{-1}).
- **Sediment load:** the total amount of sediment delivered to and transported by a stream during a specified time period, expressed as a weight (tons).

2.3 Fine sediment transfer in the fluvial system

In order to simplify the concept of a fluvial system, Schumm (1977) divides the river basin into three zones, which are illustrated in Figure 2.2:

1. The drainage basin, watershed and sediment source area. This is the area from which water and sediment are derived and forms the primary zone of sediment productions;
2. The transfer zone, where for a stable channel, the input of sediment should equal the output;
3. The sediment sink or area of deposition.

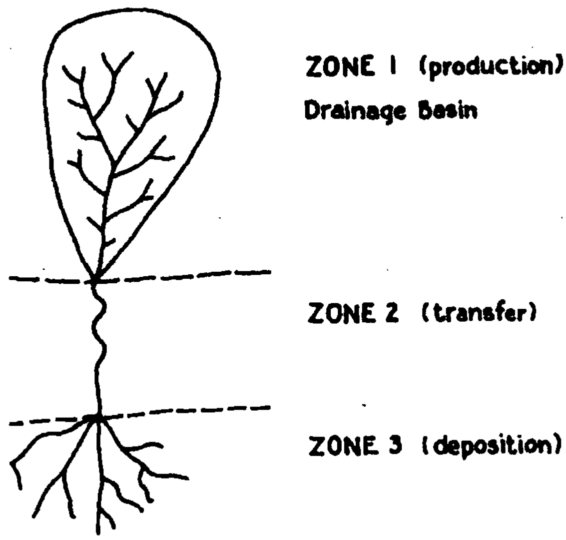


Figure 2.2: Idealised sketch showing components of the fluvial system (Source: Schuum, 1977)

Within this fluvial system, the concentration of suspended sediment, and its physical and chemical characteristic, is a function of weathering, erosion, transport and deposition at that location or upstream from that location (Knighton, 1998). These transport processes are summarised in Figure 2.3. Fine sediment is eroded from channel and non-channel sources, the rate at which is dependent on factors such as soil type, topography and vegetation cover. This mobilised sediment is then transported to the river system via a number of transport routes (e.g. overland flow, throughflow and field drains), which is then deposited within the fluvial network (Carling, 1992). The speed and position of this deposited sediment is governed by the local flow hydraulics and the particle size, shape and structural arrangement of the suspended particles (Guy, 1970). This deposited sediment is then either stored permanently or re-entrained and transported elsewhere in the river system (Knighton, 1998).

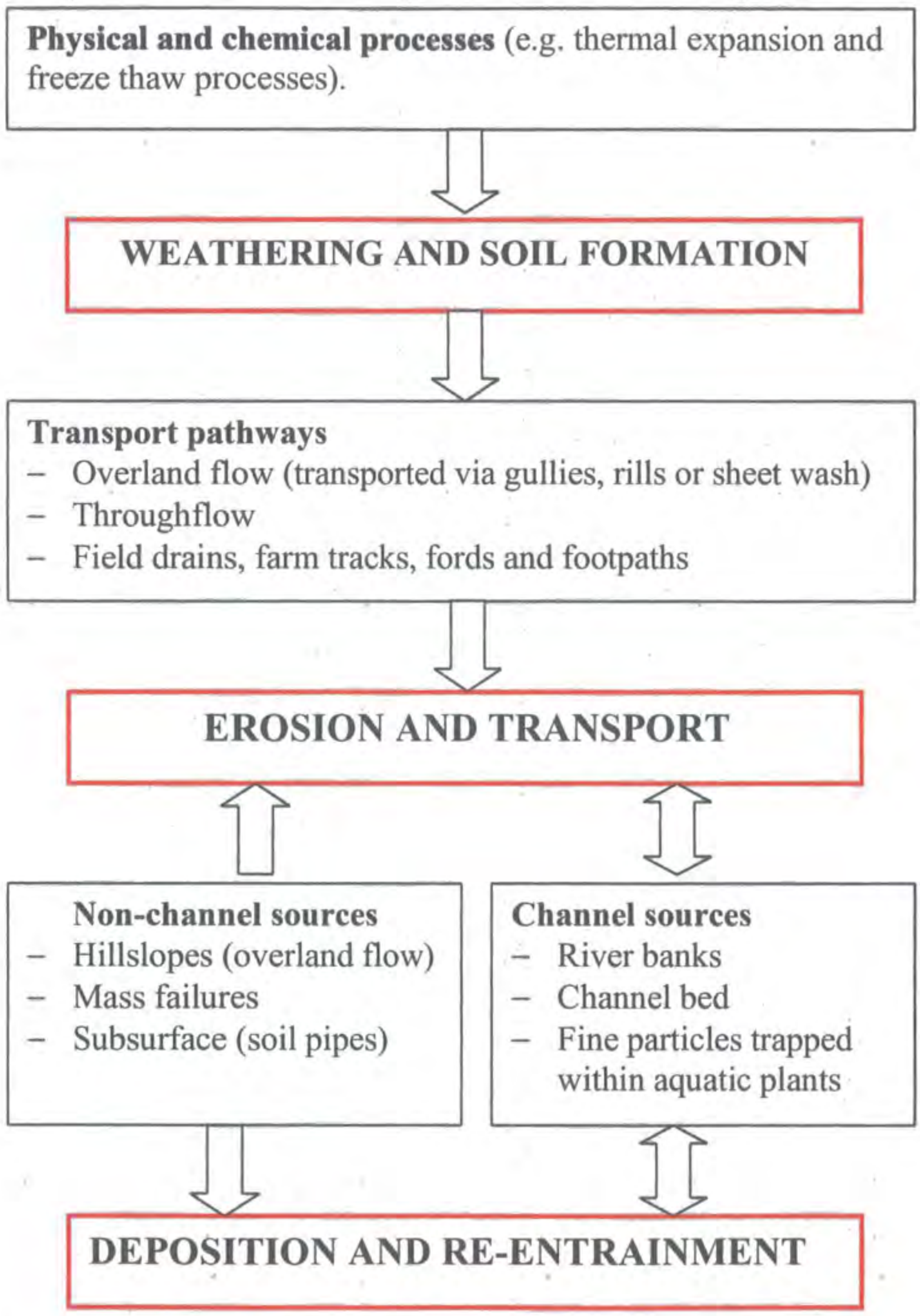


Figure 2.3: Processes of sediment weathering, erosion, transport and deposition in catchment (Source: Guy, 1970; Knighton, 1998)

2.4 Catchment controls governing fine sediment flux

The morphology and hydrology of the fluvial system, and consequently the volumes of runoff and sediment that are discharged, transferred and deposited in the fluvial system are controlled by a number of catchment variables. These are listed in Table 2.2 and are arranged in a sequence that reflects increasing degrees of dependence on other catchment variables. These controls are highly spatially variable and govern the availability of sediment in the catchment, the capacity of the flow to transport sediment and the occurrences of sediment retention mechanisms; hence control spatial patterns of fine suspended sediment flux.

Table 2.2: Catchment variables (in order of increasing dependency) (Source: Schumm and Lichty, 1965)

Drainage system variables
1. Elevation (slope gradient)
2. Geology (lithology)
3. Climate (temperature and precipitation)
4. Vegetation (type and density)
5. Relief (volume of the system above baselevel)
6. Hydrology (runoff, discharge, and sediment yield per unit area)
7. Drainage network morphology
8. Hill slope network morphology
9. Channel and valley morphology and sediment characteristics
10. Depositional system morphology and sediment characteristics

Elevation, geology, and climate are the dominant independent variables that influence the progress of the erosional evolution of a landscape, its hydrology and transport of fine sediment (1 – 3, Table 2.2). Vegetation type and density (4) depend on lithology and climate (Griffiths, 1982; Kim *et al.*, 1997) and affect suspended sediment transport by intercepting and retarding the rate of erosion and overland flow (Gurnell and Gregory, 1984). Also, the extent of the riparian vegetation affects the cohesiveness of the banks and hence its stability (Lawler *et al.*, 1997). The relief (5), or the volume of the drainage system remaining above baselevel, significantly influences runoff and sediment yield per unit area within the drainage basin (6) since it governs the amount of energy available for each stage of fine sediment transfer. The runoff in turn, acting on the soil and geologic materials, produces the characteristic drainage network morphology (e.g. drainage density, channel shape, gradient, and pattern) (7) (Williams, 1989) and hill slope morphology (e.g. slope angle, length, and profile form) (8). These morphological variables in turn strongly influence the cascading system and hence the volumes of runoff and sediment that are eventually discharged from the sediment storage areas. It is the volume and type of sediment, amount of discharge volume and flow character that largely determines channel morphology (9). Channel morphology governs the rate at which fine sediment is transferred through the system and nature of the fluvial deposits formed (10).

The size of the drainage area contributing to the sediment yield also governs the size of the sediment flux measured (Birkinshaw and Bathurst, 2006). Generally higher sediment loads are associated with larger catchments given the greater contributing areas and higher flows, causing more sediment to be released from a drainage area than the stream system is capable of removing (Crosby and DeBoer, 1995). This relationship has been studied by comparing different rivers (e.g. Milliman and Syvitski, 1992) and sub-catchments of the same river system (Lu and Higgitt, 1999). Wass and Leeks (1999) found a strong positive relationship between suspended sediment load and catchment area for the sub-catchments of the Humber system (Figure 2.4).

Although this positive relationship is found for the majority of catchments, some exhibit lower yields with increasing drainage areas. For example Griffiths *et al.* (2006) observed sediment yields from the Mojave basins (California and Nevada) to decrease as drainage area increased. The trend observed for the Mojave basin also agreed with other large basins in USA (Figure 2.5). Griffiths *et al.* (2006) concluded that this was due to the large, topographically complex nature of the Mojave drainage basins, where the sediment yield is more controlled by channel storage and transmission losses enhanced by the flat valley floors and coarse substrates, rather than drainage area. Moreover, non-uniform terrain and land use (such as increasing intensive forestry or agriculture at high elevations) causing significant inputs of sediment within the system can also complicate the relationship between catchment area and sediment yield (Small *et al.*, 2003).

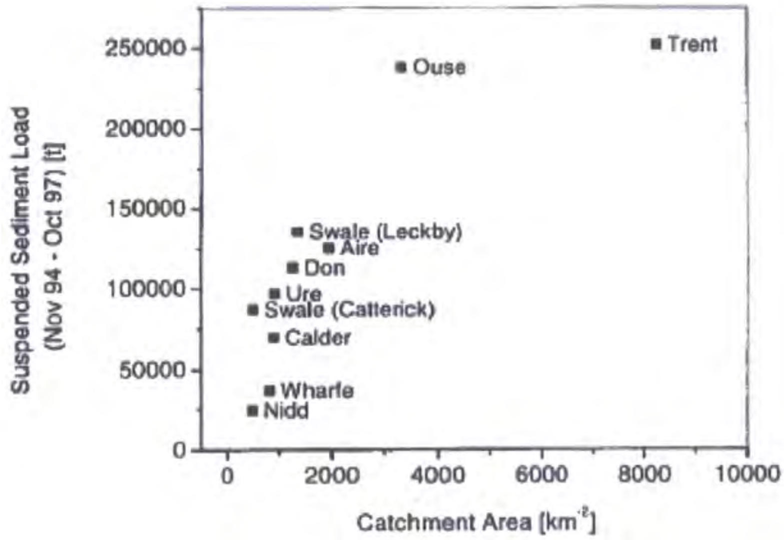


Figure 2.4: Relationship between suspended sediment load and catchment area for the main tributaries of the River Humber (Source: Wass and Leeks, 1999)

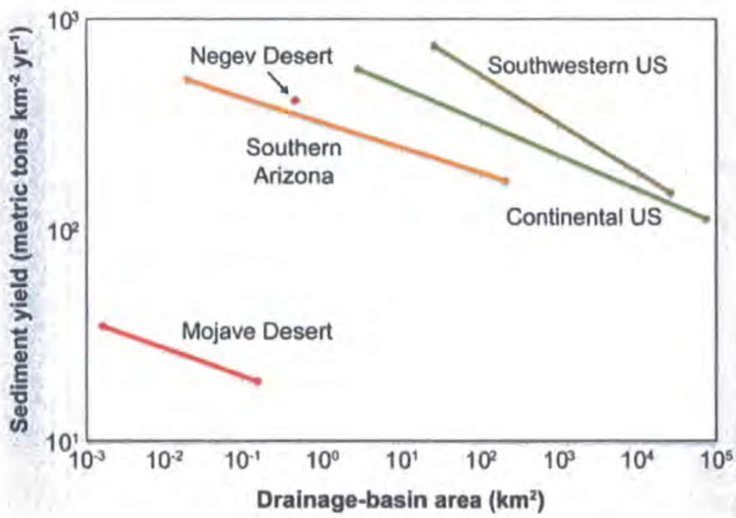


Figure 2.5: Sediment yield and drainage basins area for five different locations in USA (Source: Griffiths *et al.*, 2006)

The fluvial system can be considered at different scales: from the drainage basin; to the river reach; to a single meander; to a sand bar; to individual grains of sediment

(Schumm and Lichty, 1965). The scale used to study the fluvial system therefore greatly influences the trends and patterns of fine sediment flux observed in a catchment. No component can be totally isolated because there is an interaction of hydrology, geology and geomorphology at all scales; thus it is vital to consider the fluvial system in its entirety, even if only a small part is investigated (Green *et al.*, 1999). Moreover, due to the complex interplay between the dominant controls and sediment transport processes, it is extremely difficult to isolate and quantify the direct impact of individual catchment characteristics (Amos *et al.*, 2004).

When temporal variations are superimposed on top of these catchment controls, the complex interactions between controlling factors is further highlighted. Temporal controls generally affect sediment supply constraints and differences in meteorological and climatic conditions, but are also highly variable in response to factors such as land use and vegetation cover which are seasonally and spatially variable (Wass and Leeks, 1999). The antecedent conditions of the catchment (e.g. time since and magnitude of the last storm) in a catchment will also affect spatial patterns of sediment flux because this governs the rate at which the available sediment for transport is depleted. For example, Asselman (1999) found that the concentrations of suspended sediment in the River Rhine decreased over a runoff season, concluding that sediment depletion occurs during a hydrological year as well as during individual floods (Figure 2.6).

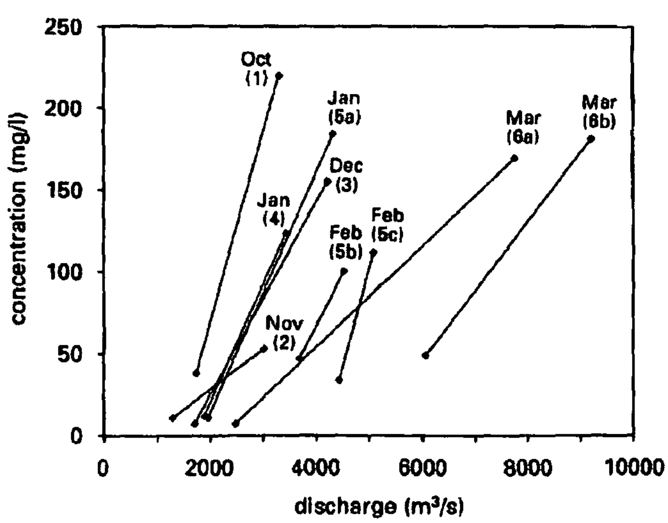


Figure 2.6: Minimum and maximum suspended sediment concentrations during subsequent floods in the hydrological year 1987-1988, measured in the River Rhine near Andernach (Source: Asselman 1999)

To summarise, there are a large number of catchment controls that govern spatial patterns of fine sediment dynamics within a catchment (e.g. topography; geology; climate; hydrology; vegetation; geomorphology and drainage area). These are widely variable within and between catchments and greatly depend on the spatial and temporal scale in which they are studied. At present, individual catchment controls have rarely been studied directly, given the difficulties in isolating and quantifying them. It is therefore essential that when investigating spatial patterns of sediment dynamics within river system, that an integrated approach is used.

2.5 Importance of documenting fine sediment flux in the British Uplands

Although there is no statutory definition for the 'Uplands' in the UK, for the purpose of this research it is taken to be 'areas above and including the upper limits of enclosed farmland containing moorland species and rough grassland' (DEFRA, 2006). By World standards, soil erosion is perceived to be of limited significance in the British Uplands and suspended sediment and load concentrations are perceived to be relatively low (Walling, 2004). In consequence, fine sediment dynamics in these Upland areas is poorly documented. Yet, it is suggested that Upland catchments are actually very important in terms of fine sediment movement and delivery and are thought to be sensitive to changes in land use management practices (Evans and Burt, 1998). In addition, hillslope to channel connectivity is widely agreed to be higher than in Lowland catchments given their typically higher gradient slopes and drainage densities of Upland catchments (Labadz *et al.*, 1991).

Examples of investigations examining sediment yields and loads in British Upland catchments do exist (e.g. Robinson and Blyth, 1982; Labadz *et al.*, 1991; Dearing, 1992; Johnson and Warburton, 2006). Labadz *et al.* (1991) investigated short and long term sediment yields on Wessenden Head Moor in Yorkshire, finding that major sources of sediment were overland flow and widespread minor gravity collapses of the steep sided gully sides. Dearing (1992) investigated longer term sediment yields and sources in Llyn Geirionydd (Welsh Upland catchment), concluding a dominance of stream channel sides rather than point sediment sources. However, there are very few British Upland based studies that investigate spatial patterns of suspended sediment flux and even fewer that attempt to identify the dominant sediment sources within the catchmemt; this can therefore be identified as a knowledge gap within the present academic literature.

2.6 Linking land use practices to spatial patterns of fine sediment flux

Human induced modifications of the vegetation cover, as a result of land use change in river basins, may cause strong geomorphic responses by disturbing sediment supply, transport and disposition regimes (Walling, 2004). The response is particularly noticeable in Upland regions, where sensitivity to change is enhanced by strong coupling between river channels and hillslopes (Section 2.5) (Labadz *et al.*, 1991). Anthropogenic disturbances have altered the British Uplands since it was first inhibited by humans. Yet, it was not until the combined effect of the agricultural revolution, rapid population growth and industrial development in 1750 when the landscape was dramatically altered (Gregory and Madew, 1982). This resulted in improved equipment, better bred animals and the introduction of crop rotation practices. Subsequently, this caused large scale conversion of grassland and woodland to arable, which was accompanied by an increase in livestock numbers and intensification of practices such as tilling and ploughing (De Boer, 1997). Agricultural procedures such as these greatly disturb the soil surface, decrease the vegetation cover, increase the compaction of the soil surface and hence decrease the infiltration rate; so enhancing runoff, detachment and transfer of fine sediment. Heathewaite *et al.* (1990) suggests that it is the decrease in organic matter levels that instigates rapid large scale erosion, since organic matter is critical for particle cohesion and the maintenance of soil stability. Conversely, Knighton (1998) argues that vegetation cover is one of the primary controls on sediment supply and catchment hydrology, and the removal of which increases the catchment sensitivity to climatic events.

Globally there are an extensive number of studies suggesting the link between erosion rates, land use change and related human activity (e.g. Gregory and Madew, 1982; Allan *et al.*, 1997; Harding *et al.*, 1998; Stott 1999; Walling, 1999; Stott *et al.*, 2001; Walling *et al.*, 2003b; Siakeu *et al.*, 2004; Stott, 2005). However, for the Upland areas examples are limited. Roberts and Church (1986) found that timber harvesting in Queen Charlotte Island mountain streams (British Columbia) caused increased sediment transport; increased sediment residence time and the accumulation of substantial wedges of coarse sediment in the stream channel. Gomez *et al.* (2001) concluded that European settlement and forest clearance between 1880 and 1920 in the Waipaoa and Waiapu rivers basins (East Coast, New Zealand) was thought to have caused increased channel aggradation and acceleration of the floodplain sedimentation rate. Furthermore, Liébault *et al.* (2005) identified the extreme sensitivity of Upland regions to land use change after studying a range of case studies from the East Coast region, North Island, New Zealand and the Southern Pre-Alps; all of which have been affected by considerable amounts of deforestation and reforestation during the last 150 years.

More specifically to Upland areas in the UK, Orr and Carling (2006) noted that intensified land use practices over the last 30 years, especially in heavily grazed hills with short vegetation cover, resulted in a more rapid runoff in the River Lune catchment, North West England. This was thought to be due to increases in stream power and the potential for geomorphic change. However increased runoff in the River Lune is also attributed to an increase in total rainfall over the last 100 years, highlighting the difficulty in differentiating the effects between climatic fluctuation and human activity, which are closely interlinked (Evans, 1990).

Other lines of evidence, however, suggest a reduction rather than an increase in suspended sediment with change in human activity. For example Siakeu *et al.* (2004) investigated the effects of contemporary human activities on SSC by examining 57 sites in Japan using governmental data and GIS. This study concluded that the majority of the measurement sites experienced decreases in SSC with time (Figure 2.7). Siakeu *et al.* (2004) concludes this to be due to reductions in area of agricultural land due to urbanisation; as well as water pollution control and erosion mitigation measures introduced since the 1970's. Kesel (1989) also notes that the suspended load of the Lower Mississippi River has decreased almost 80 % since 1850 as a result of the construction of reservoirs and dams on the Missouri and Arkansas rivers. Bathhurst and Bovolo (2004) also predict that increased afforestation will result in lower sediment yields due to higher rates of evapo-transpirations and lower runoff.

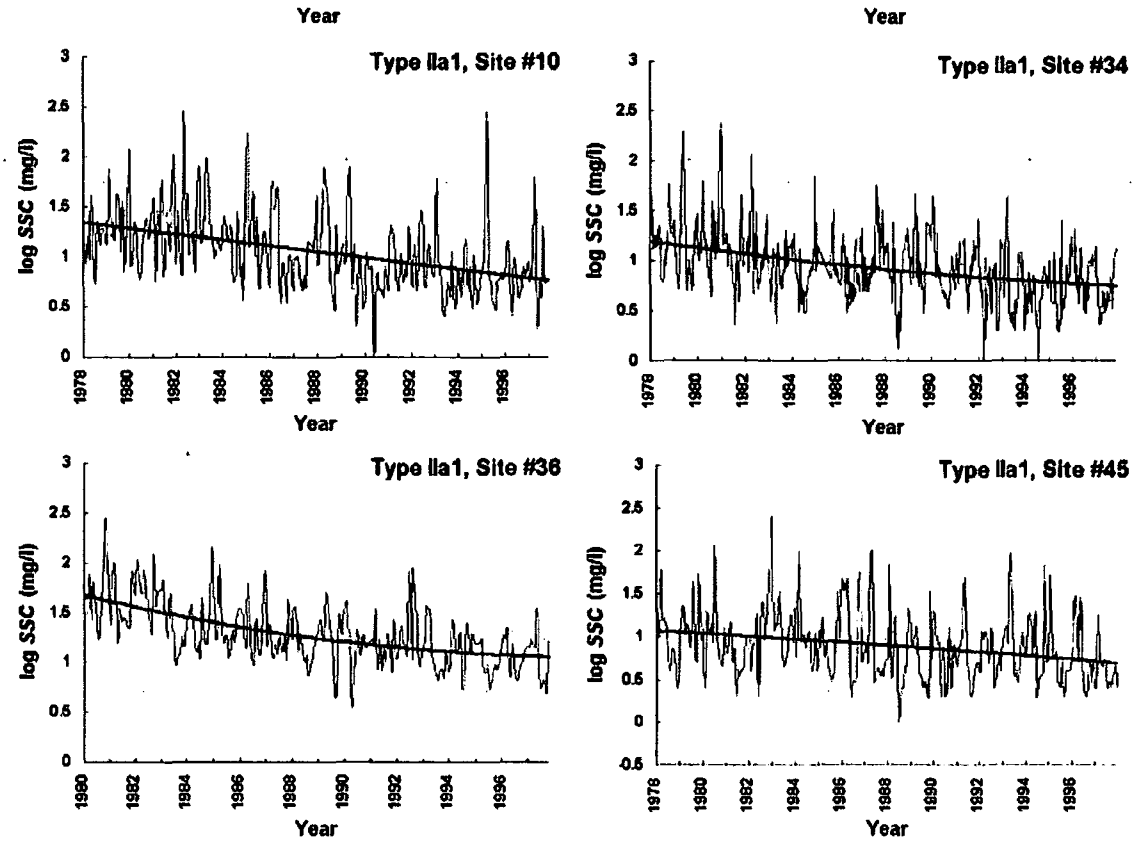


Figure 2.7: Examples of temporal changes in SSC (1980 – 1998) collected from gauging stations from rivers in Central Japan (Source: Siakeu *et al.*, 2004)

These contrasting findings highlight the complexity involved when studying the effects of land use change on patterns of suspended sediment, which are influenced by multiple interlinked processes operating at a range of spatial scales (Allen *et al.*, 1997). This is complicated further by spatial and temporal lags between the change in land use and the catchment adjusting to these changes. Moreover, most studies are limited by the lack of reliable long term records making it extremely hard to disentangle the effects of land use change and climate change (Walling, 1999). Despite these problems, it is evident that changes in land use do influence spatial patterns of fine sediment dynamics in river catchments. In particular to Upland catchments in Britain, land use changes associated with afforestation, deforestation and intensification of livestock numbers have caused an increased in fine sediment transfer in recent years (Orr and Carling, 2006).

2.7 Linking fine sediment flux with aquatic habitats

An increased input of sediment supply to Upland fluvial systems as a result of changes in land use and management practices has been found to have significant impacts upon the aquatic ecosystem. Deleterious effects of high suspended solid loads and sedimentation on riverine habitats include; smothering and killing of aquatic life; reducing light penetration, photosynthesis and primary productivity; and retarding aquatic growth and tolerance to diseases (Wood and Armitage, 1997). These detrimental effects have been well documented (e.g. Berkman and Raberi, 1987; Carling and McCohon, 1987; Davies-Colley *et al.*, 1992; Graham, 1990; Reiser, 1998).

2.7.1 Salmonids

Of particular concern in the British Uplands in recent years is the declining salmonid populations (fish from the salmon and trout family) reported for many rivers in England and Wales (Figure 2.8); especially given the amount of income brought to Upland areas as a result of salmonid fishing. This decline has been frequently attributed to the siltation of spawning gravel associated with influxes of sediment loads mobilized from recently disturbed or intensively managed land (Soulsby *et al.*, 2001).

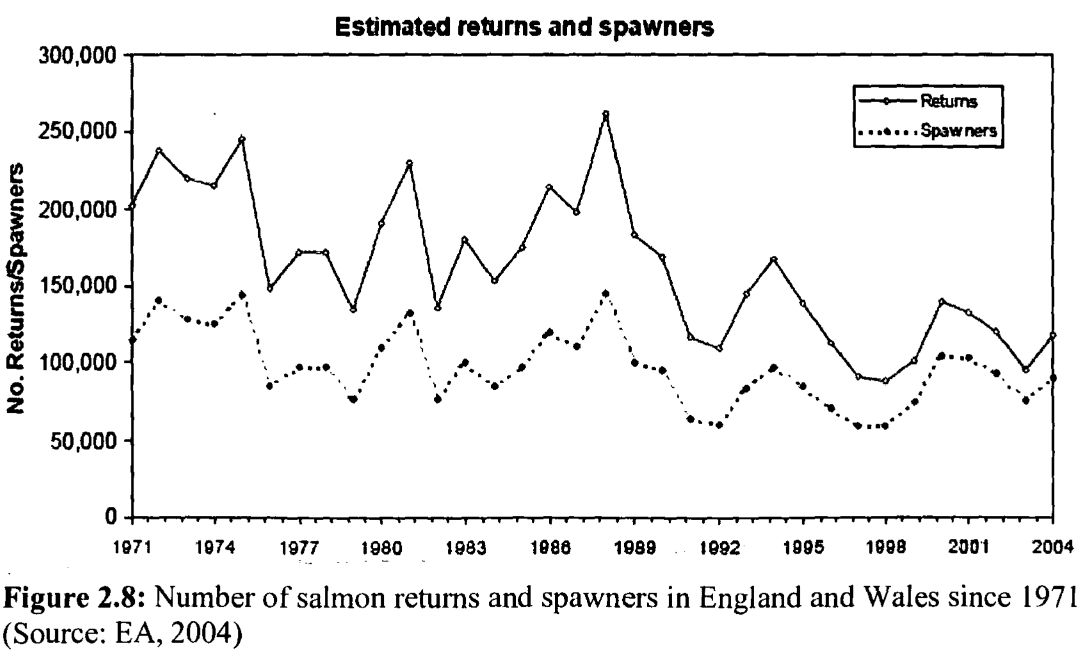


Figure 2.8: Number of salmon returns and spawners in England and Wales since 1971 (Source: EA, 2004)

Salmonids deposit their eggs in a shallow pit or redd, the location and construction of which winnows out fine sediment, thus increasing gravel permeability and intergravel flow to oxygenate the eggs. Once the eggs are deposited, they are covered with gravel (approximately 10 - 40 cm) and become part of the substrate matrix; so are subjected to interstitial hydraulic conditions (Reiser, 1998). Between two and six months are then required for the incubation of the eggs; it is during this period that the redds are extremely vulnerable to the deposition of fine sediments (Cowx and Fraser, 2003). There are many investigations providing evidence for detrimental effects of increases in fine sediment fluxes, associated with changes to land use and intensification in management practices, on salmonid populations (Table 2.3).

Table 2.3: Impacts of increased fine sediment flux on salmonid populations

Location	Findings	Author
Newmills Burn, Aberdeenshire	Increase in fine sediment in spawning gravels caused complete siltation of open gravel matrices resulting in egg mortalities of up to 86 %.	Soulsby *et al.* (2001)
River Test, River Blackwater, River Ithon, River Aran	Used artificial redds finding that incubation success is inhibited by the impact of fine sediment on gravel permeability.	Greig *et al.* (2005)
Ebbw Fawr, South Wales	Sedimentation of salmonid spawning gravels in seriously affected reaches caused 98 % - 100 % of salmonid eggs mortalities, compared to 9 % at a nearby control site.	Turnpenny and Williams (1980)
Ruby River, Montana	Increase demand for water resulted in the resuspension, transport and downstream release of fine sediment, found to kill large numbers of fish due to lamellae clogging and hypoxia.	Marks and Graham, (1997)

Although many unknowns remain in understanding the ecological and biological effects of sediment flux, transport and deposition in gravel bed rivers (Reiser, 1998), the impacts of fine sediment on aquatic habitats are thought to be more related to physical properties, such as particle size, shape and density of the suspended particles, rather than the total concentration of fine sediment (Soulsby *et al.*, 2001). Furthermore, the impacts of sediment deposition are most significant when fluvial particulate inputs correspond with periods of low flow when fine material can easily infiltrate the gravel (Leeks, 1992). However, these relatively small particulate inputs during low flow conditions, which can result in significant sedimentation impacts, are extremely difficult to observe measure and quantify.

2.7.2 Freshwater pearl mussels

In addition to decreasing salmonid populations, the recent decline in freshwater pearl mussels (*Margaritifera margaritifera* L.) in Upland catchments in the north of the UK is also causing concern among fluvial environmentalists. Freshwater pearl mussels are among the most critically endangered freshwater invertebrates. Cosgrove *et al.* (2000) estimates that of the historical pearl mussels sites occupied 100 years ago, almost 70 % are now either extinct or no longer viable (Geist *et al.*, 2003).

Figure 2.9: Freshwater pearl mussel (Source: Skinner *et al.*, 2003)

Freshwater pearl mussels are large bivalves that live at the bottom of rivers and are among the longest lived of all invertebrates, with some individuals surviving over 100 years (Bauer, 1992). The freshwater pearl has a heavy rough, compressed kidney-shaped shell (Figure 2.9). Optimum habitat conditions are cool, fast flowing waters low in calcium, on a substratum that consists of a mixture of sand, gravel, stones and boulders (Buddensiek, 1995).

Although still widely debated, it is believed that it is the intrusion of fine sediment into the microhabitat of pearl mussels, associated with increasing sediment inputs from disturbed lands in adjacent river catchments, to be one of the main factors causing the recent reductions in pearl mussel numbers (Buddensiek, 1995). The effect of excessive fine material on pearl mussels are less widely researched in comparison to salmonids, but are thought to clog the interstitial spaces, preventing the exchange of oxygen and suffocating the young mussels (e.g. Young and Williams, 1984; Buddensiek *et al.*, 1993; Hendry and

Cragg-Hine, 2003; Skinner *et al.*, 2003). Beasley and Roberts (1999) (working in rivers in County Dongeal, North west Ireland) concluded that no pearl mussels were found where the substratum was predominantly bedrock or fine sediment concentrations were high. However the direct impact of fine sediment is hard to quantify due to the difficulty in isolating individual influences from other contributing factors, such as fishing, industrial pollution and eutrophication of rivers (Cosgrove *et al.*, 2000; Hastie *et al.*, 2000; Hastie and Young, 2003).

2.8 Implications for catchment mananagement

As a result of increased fine sediment input to river channels, it is necessary that procedures are put in place to alleviate anthropogenically induced sedimentation (Heathcote, 1998). There are four main types of management options available for catchment control (Table 2.4).

Table 2.4: Management options for river catchments (Sources: Waterhouse, 1982; Novotny and Olem, 1994; Hicks, 1995; Heathcote, 1998)

Management action	Explanation and examples
1. Do nothing	Uses the concept that the catchment can buffer itself to land use change in such a way that high rates of sediment transfer will stabilise over time. It is also cheap, requires no built structures, no education programmes, easy for both decision makers and lay people to understand and disturbance to the catchment is kept to a minimum. Does not provide a 'quick fix' solution.
2. Structures/built technologies	Structural measures which include both 'end of pipe solutions and preventative options (e.g. grassed channels and waterways, runoff retention ponds, subsurface (tile) drainage)
3. Vegetative approaches	Include non-structural measures that change the extent, nature and/or timing of the vegetation cover therefore change the rate and quality of the water flowing over the land surface, readily controlled by the farm operator, often low in cost and provide secondary benefits such as increased crop productivity (e.g. filter strips and buffer zones, critical area planting, crop rotation)
4. Best management practises	Non-structural measures which can be low-cost and highly effective, yet harder to implement as they depend on public participation and co-operations (e.g. contour ploughing, livestock exclusion range management, property site selection for animal feeding, appropriate stocking rates).

However, in view of the complex, diverse nature of river catchments, there has been increasing popularity in using a combination of management options; for example vegetative approaches (e.g. a riparian buffer strip) in combination with best management practices (e.g. riparian fencing) can be used to control livestock poaching in agricultural areas (Heathcote, 1998).

The spatially distributed nature of soil erosion and sediment delivery, as well as a variety of possible soil conservation and sediment control measures requires an integrated approach to catchment management (Vertraeten *et al.*, 2002). Examples of existing integrated catchment management plans in Upland catchment include: the Moorland Vision and Dartmoor Hill Farming Project (DNPA, 2005); the integrated pilot scheme for the Brecon Beacons National Park (Steven and Associates, 2002); and the Annan Catchment Co-ordination Project in Dumfries and Galloway, Scotland (Griffin and Coutts, 2001). However, successful implementation of integrated catchment plans on a large scale is relatively limited

On a smaller scale, agri-environmental schemes have been established in the Upland areas to encourage lower stocking levels and more appropriate management practices, in an attempt to promote sustainable agriculture management of the Upland heathland (DEFRA, 2006). Such examples include:

1. Implementation of environmentally sensitive areas in the Lake District, North Peak, South West Peak, Exmoor and the Shropshire Hills;
2. 42,000 ha of Upland heath areas in the UK have been notified as Sites of Special Scientific Interest (SSSIs);
3. Livestock support mechanisms are being reviewed and modified in for Less Favourable Areas (LFAs)).

Furthermore, organisations such as DEFRA and EA are funding research examining the influences of land use changes and possible procedures to alleviate such affects in Upland areas. Some of the topics currently being researched include;

1. The effects of extensification of grassland use in the Uplands;

2. The success of re-establishing dwarf shrubs which have greatly declined over the last 30 years due to burning/overgrazing;
3. The effects of moving feeding blocks away from vulnerable areas;
4. Examining bracken control and vegetation restoration;
5. The establishment of environmentally sustainable and economically viable grazing systems for restoration and maintenance of heather moorland.

(DEFRA, 2006).

However, at present, there is a poor transfer of information between the researchers and practitioners, making this research of limited use in management terms. These management strategies are unsuccessful where the catchment managers meet resistance from the farm operator wanting to uphold traditional farming methods and are reluctant to risk lower productivity. Co-operation and involvement of all landowners and local communities, good leadership and adequate training are crucial to ensure that projects are sustained beyond construction (Goodman and Edwards, 1992). Moreover, many interventions are planned in an *ad hoc* manner with inadequate data and knowledge of the physical settings, such as the hydrology, geology, meteorology. For such interventions in catchments to be successful, it is vital that they incorporate the hydro-meteorology and geomorphology characteristics of the individual watershed, which must not be stereotyped, but should be designed to suit specific physical and socio-econmic environment (Palanisami *et al.*, 2002). Consequently, it is critical that effective research data, in the form of suspended sediment yields and mapped catchment characteristics, are obtained for the successful design of specific and cost effective, integrated catchment management (Palanisami *et al.*, 2002).

2.9 Monitoring spatial variability in fine sediment flux

2.9.1 Fine sediment flux

The literature discussed so far highlights the need for measuring and documenting patterns of fine sediment flux within a river catchment; essential for the construction and implementation of effective target catchment management strategies. Several such studies exist (e.g. Walling, 1990; Walling and Woodard, 1992, Collins *et al.*, 1997b; Jarvie *et al.*, 2002). Key to an accurate understanding of fluvial fine sediment dynamics is the need to obtain representative, spatially variable suspended sediment loads (Walling, 2004). Such information is difficult to assemble and requires a carefully designed monitoring programme aimed explicitly at generating reliable suspended sediment load data.

Across most of the UK the information on suspended sediment transport is limited to data provided by standard water quality sampling programmes based on regular sampling at weekly or even monthly intervals (e.g. Walling and Webb, 1988; Phillips *et al.*, 1998). Yet these are very limited in that it is unlikely that such sampling programmes sample infrequent high flow events, when both concentrations and flows are at their highest; hence are the most significant periods in suspended sediment transport (Russell *et al.*, 2000). Thus, sediment loads estimated from infrequent samples are deemed as inaccurate and imprecise (Walling, 2004). Most of the existing studies of suspended sediment flux in the UK focus on measuring the load at the catchment outlet, in order to provide a spatially lumped estimate of sediment yield (i.e. t km^{-2} $year^{-1}$) (e.g. Grunwald and Frede, 1999). However, recognition of the wider environmental significance of fine sediment mobilisation, transfer and storage has directed attention to the internal functioning of the catchment and the need to obtain information on sediment sources and sediment transfer pathways. These considerations can be usefully considered in a catchment sediment budget (Rosati, 2005) which identifies sources, transfers and sinks within a river basin (e.g. Trimble, 1983; Walling *et al.*, 2002).

Sediment budgets link processes in Upland areas with sediment delivery downstream using a mass balance equation approach (Trimble and Crosson, 2000). However these approaches are limited because most of the sampling programmes that characterise sediment budget investigations incorporate small numbers of sampling sites which are poorly distributed to estimate sediment delivery during storm events (Reid and Dunne, 1996).

In recognition of the problems associated with collecting accurate spatial estimates of fine sediment flux for a catchment, Phillips *et al.* (2000) proposes a simple sampling strategy, using Time Integrated Mass Samplers (TIMS). TIMS have the advantage of allowing suspended sediment to be measured continuously by collecting *in situ* bulk fine sediment samples, providing estimates of lumped storm yields which can be distributed throughout the catchment to capture spatial variability of suspended sediment transfer (Russell *et al.*, 2000).

2.9.2 Stream reconnaissance surveys

A criticism of the fine sediment flux studies outlined above is that they do not consider the processes and catchment controls that link these fine sediment transfers from the land to the channel (Figure 2.2). The linkage between the hillslope and river is crucial in management terms since it allows problems areas in terms of contributing large amounts of fine sediment to the river systems in the catchment to be identified. Stream reconnaissance surveys are being increasingly used to produce fine sediment audits which identify dominant areas of bank failures and significant sediment inputs along the main channel and tributaries (e.g. Walling and Woodward 1992; Collins *et al.*, 1997c; Thorne, 1998; Walling *et al.*, 1999b). These reconnaissance surveys can then be coupled with a desk based assessment to generate a larger scale assessment of catchment controls using a series of coverages (e.g. land use, geology, topography, vegetation cover).

For example, Walling *et al.* (2003a) carried out a reconnaissance survey to establish the dominant source and locations of fine interstitial sediment recovered from spawning gravels in 18 important salmonid rivers in England and Wales. Another example of a channel reconnaissance study was that of the 'Catchment Fluvial Geomorphological Audit of the Esk Catchment' (2004) by Babie Brown and Root, commissioned by the EA. The main objective of the survey was to create a fluvial audit to inform a range of catchment initiatives. Although reconnaissance surveys, such as these, have the advantage of providing a large-scale overview of catchment characteristics and provide an indication of possible dominant source areas and mechanisms of fine sediment transfer (Thorne, 1998), they provide no means of monitoring and assessing fine sediment dynamics before, during and after catchment initiatives have been implemented. In terms of fine sediment transfer, therefore, these predominantly qualitative surveys do not quantify the effects of such strategies on fine sediment loads and yields.

It is therefore necessary to incorporate spatial patterns in fine sediment flux (for example data collected from TIMS samplers (Phillips *et al.*, 2000)) with that of a reconnaissance surveys, which map both small and large scale catchment controls. Examples of surveys that have achieved such a task are relatively limited, but the ability, ease and flexibility to do so have been increased in recent years with the advent and development of Geographical Information Systems (GIS). GIS allows a series of spatial data (e.g. spatial patterns of fine sediment, bank material geology and topography) to be combined and analysed with ease and is being increasingly used in catchment based investigations (e.g. Downward *et al.*, 1994; Aspinall and Pearson, 2000; Jarvie, 2002; Siakeu *et al.*, 2004). The use of GIS is therefore an invaluable tool in implementing catchment management as it allows the integration of large amounts of data, of varying spatial scales, which cover large areas, to be readily and easily analysed (Bocco *et al.*, 2001).

2.10 Identifying dominant sediment source areas

There is increasing need for accurate information on sediment provenance, especially from a management perspective since identification of sediment sources, and therefore linkages to specific land use management practices, is a key precursor to the design of effective sediment management and control strategies (Walling *et al.*, 1999b; Collins and Walling, 2004). Sediment sources exert a key role on both the physical and geochemical properties of fine sediment, which in turn governs the magnitude and spatial pattern of fine sediment fluxes (Walling, 1999; Walling, 2005). Therefore the suspended sediment load transported by a river will commonly represent a mixture of sediment derived from different locations and from different source types within the contributing basin (Collins and Walling, 2004).

For example, the grain size composition of suspended sediment reflects both the nature and relative importance of the various sediment sources within a catchment (Walling and Moorehead, 1989; Lenzi and Marchi, 2000). Sediment mobilized from channel bank sources may, for example, be appreciably coarser than that mobilized from the catchment surface. Therefore an increase in the relative contribution from channel sources could results in suspended sediment with a coarser grain size distribution. For example Walling *et al.* (2000) concluded, after finding considerable variation between spatially distributed sampling sites within the Ouse basin (ranging from 4.3 μm (River Wiske) to 13.5 μm (River Burn)), that the finer particle grain sizes associated with the River Wiske (4.3 μm) could reflect a reduced contribution from channel bank sources and a more gentle topography. However, spatial distributions of grain size of suspended fluvial material is also influenced by chemical and physical alteration, and size selective processes during transport; limiting the extent to which particle size can be used to identify dominant source areas (Bogen, 1992; Gruszowki *et al.*, 2003).

To ascertain the key source areas in a catchment more conclusively, a 'fingerprinting' approach to identify dominant source provenance has been being increasingly applied. Two basic steps underline the application of sediment fingerprinting: Firstly the selection of diagnostic physical and chemical properties which are capable of discriminating potential sediment sources in an unequivocal manner: Secondly, comparison of measurements of the fingerprinting properties obtained for suspended sediment samples with the corresponding values for source material samples (Collins *et al.*, 1997a; Walling *et al.*, 1999b; Minella *et al.*, 2004). As yet there is no general agreement about the characteristics, but the selection of suitable diagnostic properties should depend on the nature of the potential sources to be distinguished and the drainage basin characteristics (Walling *et al.*, 1999a).

Single diagnostic fingerprinting methodologies using one tracer characteristic were firstly developed. Such examples include the use of fallout radionuclides (e.g. caesium 137 (^{137}Cs); lead 210 (^{210}Pb); and beryllium 7 (^{7}Be) (Peart and Walling, 1986); plant pollen (Brown, 1985); mineral-magnetic properties (Slattery *et al.*, 1995); and metal content (Benoit *et al.*, 1999) sediment properties to identify dominant sediment source provenance. For example, Grimshaw and Lewin (1980) used the colour of the yielded suspended sediment to identify dominant sediment source areas for the River Ystwyth catchment (mid-Wales). This was done by adding colours of suspended sediment samples to a discharge-concentration plot to identify distinct zoning of colours (Figure 2.10).

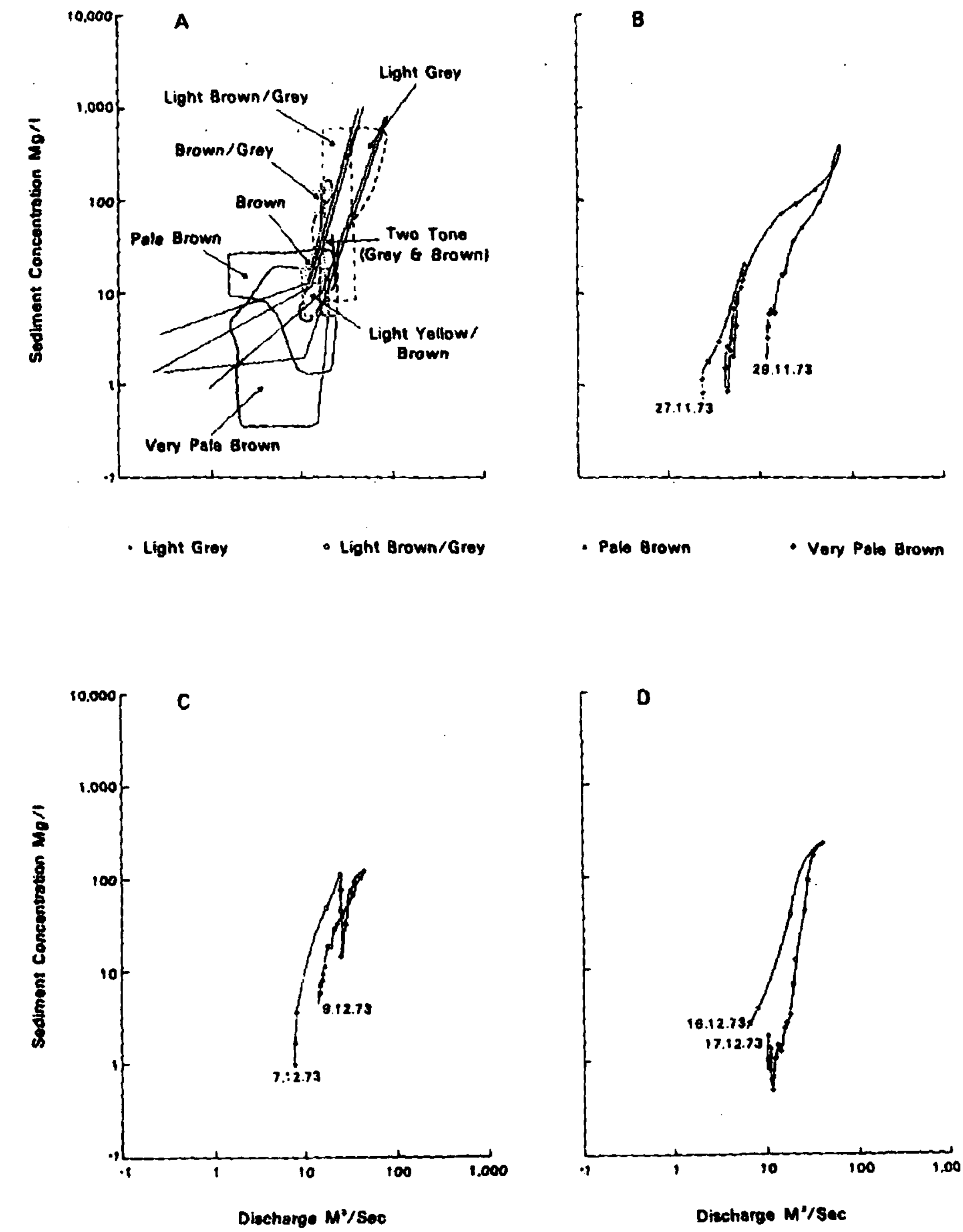


Figure 2.10: Suspended sediment-discharge relationships and sediment colour: (A) colour zones and fitted regression relationships; and (B), (C) and (D) sediment loops and colour sequences for selected events (Source: Grimshaw and Lewin, 1980)

A sequence of colour changes were then observed for individual runoff events finding light-brown/grey sediment colours dominant as the stage rises. The colour appeared in reverse order on the falling stage. Grimshaw and Lewin (1980) concluded that these two major colour types represented the two dominant source types contributing to the Ystwyth catchment. Although in criticism of this study, only qualitative indications of dominant sediment source areas, which are surrounded by a large amount of uncertainty, are provided rather than more quantitative estimations of source area contributions (Walling, 2005).

Walden *et al.* (1997) uses mineral magnetic data to successfully identify the relative sediment source contributions to suspended sediment loads within the Stour River system (Figure 2.11).

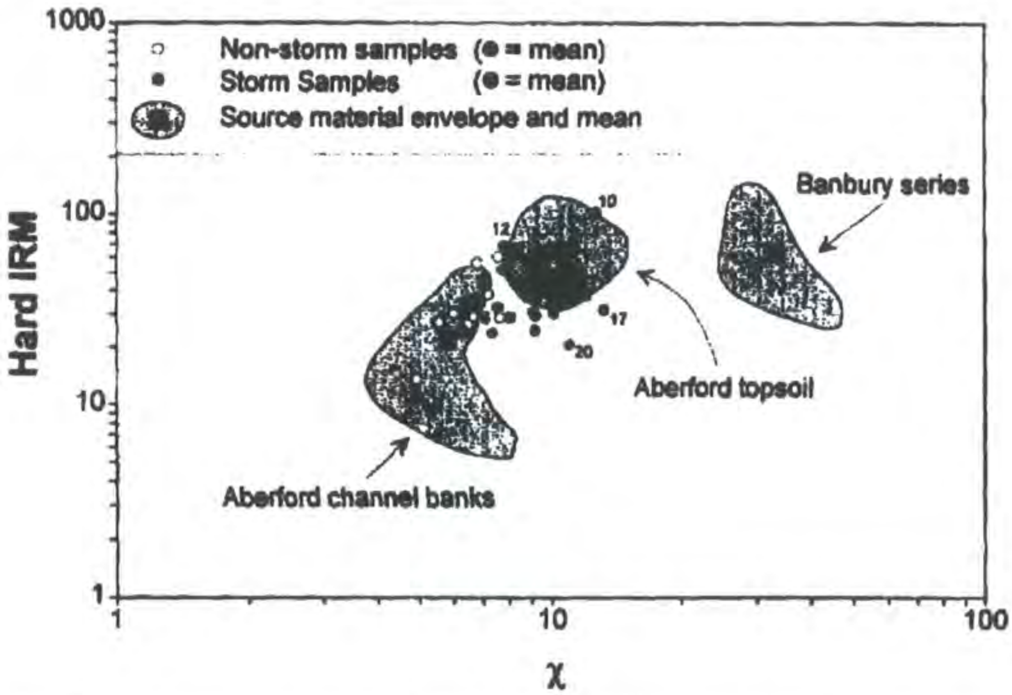


Figure 2.11: Plots of magnetic susceptibility (10^{-7} m^3 kg^{-1}) vs. hard isothermal remanence magnetic susceptibility (IRM) for the catchment source and suspended sediment samples in the Stour River system (Source: Walden *et al.*, 1997)

Moreover, Walden *et al.* (1997) demonstrates the feasibility and potential of providing more quantitative sediment source ascription using a sediment 'unmixing' model based upon a linear programming algorithm. In brief, this 'unmixing' model essentially carries out an iterative search to find optimum combinations of the source material, which when linearly mixed, minimised the differences between the measured magnetic properties of the suspended sediment and the magnetic properties of the mathematical mixture of the sources. This model can then be run using the Solver 'add in' component of Microsoft's Excel by supplying the properties of the source materials, the measured properties of the suspended sediment sample which has to be 'unmixed' and the initial starting proportions of each source from which the optimisation routine will move to fine the 'best' solution (Walden *et al.*, 1997).

However, the scope of the studies discussed above, that use single diagnostic properties (e.g. Grimshaw and Lewin, 1980 (sediment colour); Walden *et al.*, 1997 (magnetic properties)) are limited in discriminating unequivocally between several potential sources (Walling, 2005) and may be unreliable because of spurious source-sediment matches (Collins and Walling, 2004). Subsequently, there has been an increased attention upon the use of composite, rather than single-component signatures, incorporating a range of properties. Composite fingerprints increase the reliability of the results obtained and permit the discrimination of a greater range of potential sources (Walling *et al.*, 1993). Such fingerprinting studies include: Qu *et al.* (1995); Walling, (2005) and; Owens *et al.* (2005). For example Krien *et al.* (2003) successfully identified dominant sediment sources in the Olewiger Bach drainage basin (western Germany) using a combination of loss on ignition measurements, the determination of fine sediment fractal dimensions and particle colour.

Collin *et al.* (1997b) effectively quantified suspended sediment sources in the Upper Severn catchment using a composite of trace metals base cations, organic and grain size distribution measurements. This was done using a two-stage statistical procedure to find optimum sets of source material and sediment properties. A multivariate sediment mixing model was then used in conjunction with the statistically selected composite fingerprints, to estimate and quantify present relative contributions from individual sediment source types to the sediment loads. Other studies that have used similar mixing models to quantify the provenance of recent fluvial sediments are summarised in Table 2.5.

Table 2.5: Examples of fingerprinting investigations in the UK that use mixing models to quantify sediment source provenance

Location	**Findings**	**Author**
River Dart	Fallout radionuclides concentrations (^{137}Cs ^{210}Pb ^{7}Be) offer considerable potential as fingerprinting properties as there are independent of lithology and soil type.	Walling and Woodward, (1992)
River Eve and Severn	Successful fingerprinting techniques demonstrating surface erosion of pasture soils to be the dominant sediment source.	Collins *et al.* (1997a)
River Ouse and River Wharfe	Found channel banks were the greatest contributor to suspended sediment samples collected at high flows.	Walling *et al.* (1999b)
River Ouse, Yorkshire	Used fingerprinting to identify the contributions to total suspended sediment flux from different topographical and geological zones.	Walling *et al.* (1999a)
Rosemaund catchment; The Smisby catchment	Relative contributions of potential sediment sources were established, using fingerprinting properties, finding field drains accounted for 27-55% of the sediment yields.	Russell *et al.* (2000)
Upper Torridge catchment in Devon	Used heavy metals, trace metals and base cations, organic carbon, nitrogen and grain size distribution suggesting that pasture areas were the dominant sources of suspended sediment	Walling, (2005)

Despite the success of studies that use 'mixing' and 'unmixing' models to quantify dominant source areas, there still remain substantial methodological uncertainties, such as: errors in possible source definition; chemical alteration during transport; the presence of size selective transport and enrichment of the sediment relative to the source material; and transformation of sediment properties due to the erosion, transportation or deposition processes operating within the fluvial systems (Walden *et al.*, 1997). Provenance ascription can also be criticised for being necessarily crude and the interpretation of which is rendered difficult; especially in larger catchments as consideration of spatial provenance avoids the inherent complexity in the spatial distribution of individual source types (Collins *et al.*, 1997a).

Furthermore, large inter-storm variations in sediment source type reflect antecedent conditions, variable contributing areas and timing of sediment sample collection, resulting in the importance of the individual sediment sources to vary from event to event, and even within events (Walling and Woodward, 1992). This highlights the individuality of catchment response for a particular flood event, emphasizing the necessity for detailed sampling programmes of suspended sediment in storm periods covering a range of seasons and event magnitudes. Additionally, further work is required to provide a basis for recommending sets of fingerprint properties for particular applications. Despite these limitations, the potential of identifying dominant source areas within a catchment, by comparing a composite of measured properties of suspended sediment with that of possible sediment source materials, can be recognised.

2.11 Chapter summary

Recent changes to land use management practices, such as increased intensity of agriculture, afforestation and deforestation, have caused increased fine sediment inputs from the catchment (e.g. Stott 1999; Allan *et al.* 1997; Orr and Carling, 2006; Siakeu *et al.*, 2004; Liébault *et al.* 2005). This increase in fine sediment is widely agreed to be having detrimental impacts on aquatic habitats (e.g. Reiser, 1998; Cosgrove *et al.*, 2000; Skinner *et al.*, 2003). Catchments in the British Uplands are of particular concern since these are considered to be the most sensitive to such changes (e.g. Labadz *et al.*, 1991; Dearing, 1992; Liébault *et al.*, 2005) and are home to important aquatic habitats such as salmonid species and freshwater pearl mussels (e.g. Beasley and Roberts, 1999; Soulsby *et al.*, 2001). Consequently catchment management plans targeting hotspots in fine sediment and dominant source areas are increasingly required (Hicks, 1995; Heathcote, 1998; Palanisami *et al.*, 2002).

However, to inform successful management strategies, there is a need develop methodologies that accurately monitor and document fine sediment flux and associated catchment features (Downward *et al.*, 1994; Thorne, 1998; Phillips *et* al., 2000; Walling, 2004). The integration of large amounts of spatial data within in a GIS framework has the potential of creating detailed databases which can be used as a tool to inform of fine sediment characteristics target management initiatives (Downward *et al.* 1994; Jarvie, 2002). Additionally there is a management need to identify key sediment source locations within a catchment and a 'fingerprinting' methodology can be recognised as having the potential to do so (Collins *et al.*, 1997b; Walden *et al.*, 1997; Walling *et al.*, 2003a; Collins and Walling, 2004; Walling, 2005).

Chapter Three: STUDY SITE

3.1 Overview

The Upper Esk catchment in the North York Moors, North England provides an ideal location for studying changes in patterns of fine sediment supply, transfer and delivery in relation to changes to recent changes in land use management. It is representative of UK temperate Upland catchments and therefore will be able to add to the, limited database on suspended sediment characteristic of UK Upland catchment. The purpose of this chapter is to outline the physical setting of the River Esk catchment and the implication this has on spatial patterns of fine sediment dynamics (Sections 3.2 – 3.6). Following on from this, the ecological significance, land use and management initiatives present in the Esk are examined (Section 3.7 – 3.9). Lastly, the chapter is summarised by discussing the representativeness of the Esk catchment in comparison to other Upland catchments and as a pilot catchment for Upland management studies and projects (Section 3.10).

3.2 Location

The River Esk catchment (362 km^2) is situated on the North East Coast of England (Figure 3.1). The River Esk rises on Westerdale Moor at an altitude of 370 m in the North York Moors National Park and flows east to west, for approximately 42 km, to its mouth at Whitby on the North Sea. The Esk catchment can be split into three main sections; the Upper Esk, the Middle Esk and the Lower Esk. For the purpose of this study it is the Upper Esk, the most western part of the catchment that flows from Westerdale to Grosmont, that shall be studied. This area of the catchment includes the main tributaries; Commondale Beck; Baysdale Beck; Westerdale Beck; Tower Beck; Danby Beck; Great Fryup Beck; Glaisdale Beck; Butter Beck; Eller Beck and Murk Esk (in order downstream). Catchment areas are summarised in Table 3.1.

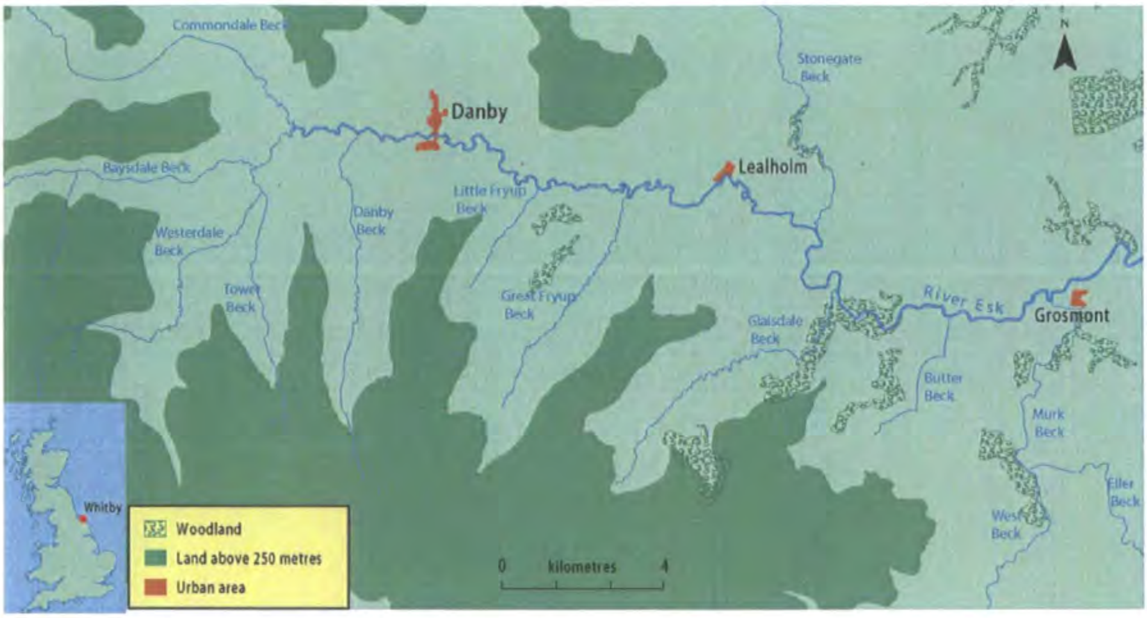


Figure 3.1: Location of River Esk catchment and main tributaries

Table 3.1: Catchment area (in size order) of the main tributaries and Main Esk sampling sites in the Upper Esk catchment

Tributary	Catchment Area (km^2)	Tributary	Catchment Area (km^2)
Tower Beck	6.71	West Beck	42.99
Butter Beck	8.79	Esk at Six Arch Bridge	98.88
Danby Beck	12.06	Esk at Danby (A)	107.49
Great Fryup Beck	14.47	Esk at Danby (B)	107.49
Glaisdale Beck	15.38	Esk at Duck Bridge	114.73
Baysdale Beck	17.10	Esk at Lealholm	143.57
Westerdale Beck	18.57	Esk at Glaisdale	186.81
Commondale Beck	25.01	Esk at Egton Bridge	199.44
Eller Beck	31.93	Esk at Grosmont	297.24

3.2 Glacial history

The Esk valley has been considerably altered as a result of glacial activity and ice advances in the Quaternary Period (during the last 2 Ma) and glacial melt-waters have eroded spectacular channels, particularly downstream of Lealholm (Morley, 1997). It has been hypothesised that thick ice prevented streams and rivers reaching the lowlands and melt-water accumulated in many moorland valleys, such as in the Upper Esk valley upstream of Lealholm, where the broad flat valley floor is thought to be have once been occupied by a glacial lake (Eskdale Lake) (Figure 3.3) (Stainforth, 1993). When glacial drainage levels reached the lowest points in the surrounding hills these glacial lakes overflowed and drained away in directions totally opposed to normal drainage patterns creating the present day unique Esk drainage pattern. A characteristic of these overflow channels is that they are extremely steep and narrow, creating flashy flood peaks which have the capacity to transport large amounts of fine sediment.

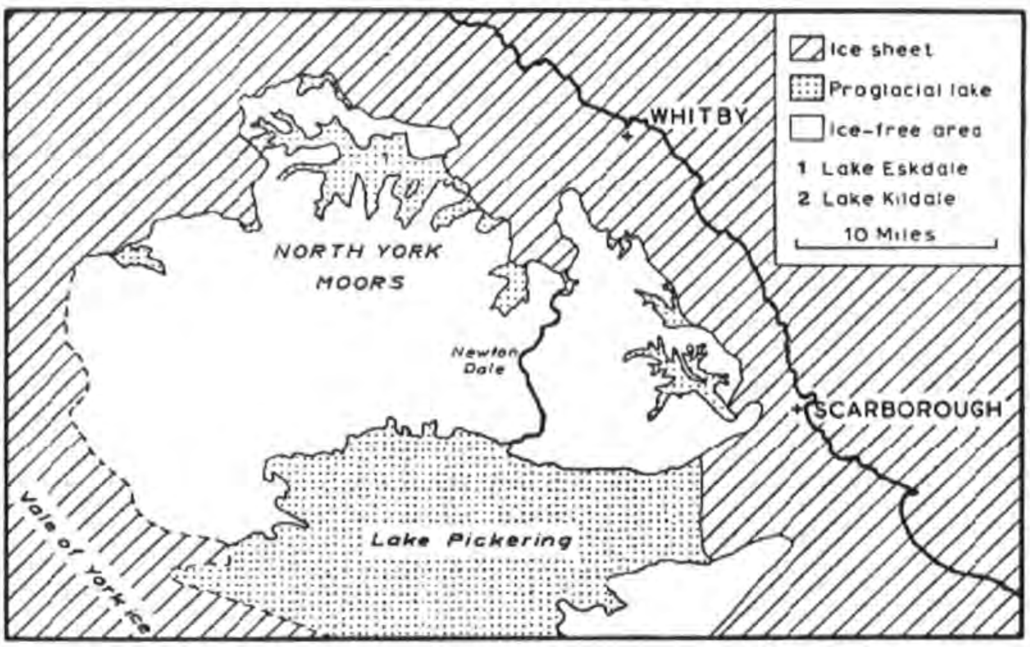


Figure 3.2: Proglacial lakes in north-east Yorkshire (Source: Gregory, 1965)

3.3 Relief

The elevation and slope gradients in the Esk catchment are highest for the southern headwater tributaries, such as Tower Beck, Danby Beck and Great Fryup Beck, which have average slope gradients of 4.28 %; 3.38% and 2.98 % respectively (Figure 3.3 and Table 3.2). This suggests that during storm events and periods of high flow, these sub-catchments have the ability to mobilise and transport large amount of fine sediment to the River Esk network. In comparison, the tributaries to the east, such as Eller Beck and the Murk Esk exhibit much lower elevations and gentler slope gradients (1.57 % and 1.27 % respectively) and implies that these tributaries are less significant in supplying fine sediment.

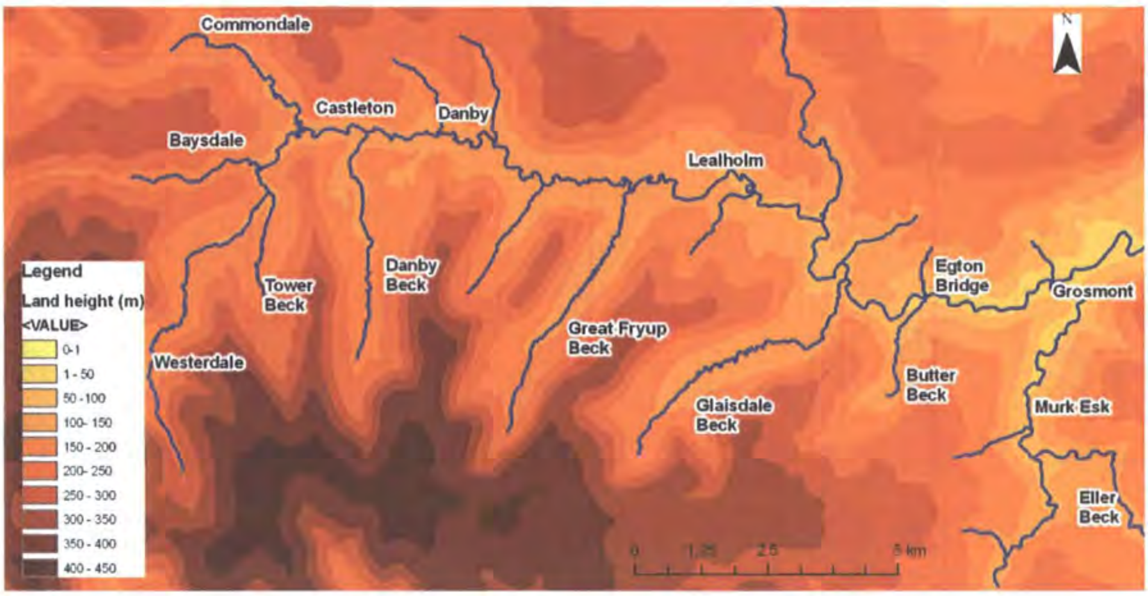


Figure 3.3: Land elevation (m) of the Esk catchment

Table 3.2: Average channel gradients for the main tributaries of the River Esk

Tributary	Average gradient (%) (mm^{-1})	Tributary	Average gradient (%)(mm^{-1})
Tower Beck	4.28 (0.04)	Commondale Beck	1.15 (0.01)
Butter Beck	3.75 (0.04)	Eller Beck	1.57 (0.02)
Danby Beck	3.38 (0.03)	Murk Esk	1.27 (0.01)
Little Fryup Beck	4.95 (0.05)	Esk at Commondale to Dibble Bridge	0.53 (0.01)
Great Fryup Beck	2.98 (0.03)	Esk at Castleton to Lealholm	0.20 (0.002)
Glaisdale Beck	1.76 (0.02)	Crunkly Gill (near Lealholm)	1.08 (0.01)
Baysdale Beck	1.55 (0.02)	Esk at Lealholm to Glaisdale	0.69 (0.01)
Westerdale Beck	2.07 (0.02)	Esk at Glaisdale to Grosmont	1.11 (0.01)

In most river systems the channel widens and the gradient lowers downstream. However in reverse of this usual trend, due to the glacial history of the area (Section 3.2), the River Esk between Castleton and Lealholm has an unusually low gradient (0.20 %) with a meandering planform which flows within a 200-300 m wide floodplain; whereas downstream of Lealholm to Egton Bridge, the channel gradient steepens (0.61%) and the River Esk is contained with steep valley sides and relatively narrow floodplains. Downstream of Egton Bridge the river becomes gentler and the floodplain widens (EA, 2004). This irregular planform will therefore have implications on the dominant locations of fine sediment transfer, delivery and deposition in the river Esk catchment.

It is the steep headwater tributaries, which have narrow floodplains, that makes the Esk an especially flashy system, as floodwaters are rapidly funnelled through the Upper basin during high flow events. Extensive flooding then occurs where these floodwaters overspill into the wider, gentler floodplains upstream of Lealholm. This is illustrated in Figure 3.4, an aerial photograph showing the extent of flooding near Lealholm during the large summer flood in 2002.

Figure 3.4 River Esk in flood upstream of Lealholm during the summer of 2002 (Source: EA, 2005)

3.4 Geology

The geology of the North York Moors is dominated by rocks of the Jurassic age. The earliest deposits belong to the dominantly marine Lias Group (268-188 Ma) and include fossiliferous mudstones, shales and sandstones (Morley, 1997). These are predominantly found in the southern headwater tributaries (Figure 3.5). Owing to the comparatively softer and more easily erodible nature of these early deposits, where glacial activity has removed more recently formed rock layers, could potentially represent dominant areas of fine sediment inputs into the Esk river system (EA, 2005).

The Lias Group is overlain by the Middle Jurassic Ravenscar Group (178-157 Ma) which is dominated by sandstone with some limestone and mudstone. This mid Jurassic strata underlies much of the North York Moors and is responsible for the characteristic moorland scenery and acidic soils. The Upper Jurassic (157-145 Ma), which consists of Corallian Group limestones and sandstones, makes up the uppermost layer and is overlain by Oxford Clay. These harder sandstone forms the edges or cliffs to the valley sides where streams have cut deep valleys and slopes through softer Lias shales, creating the dramatic scenery evident in the North York Moors.

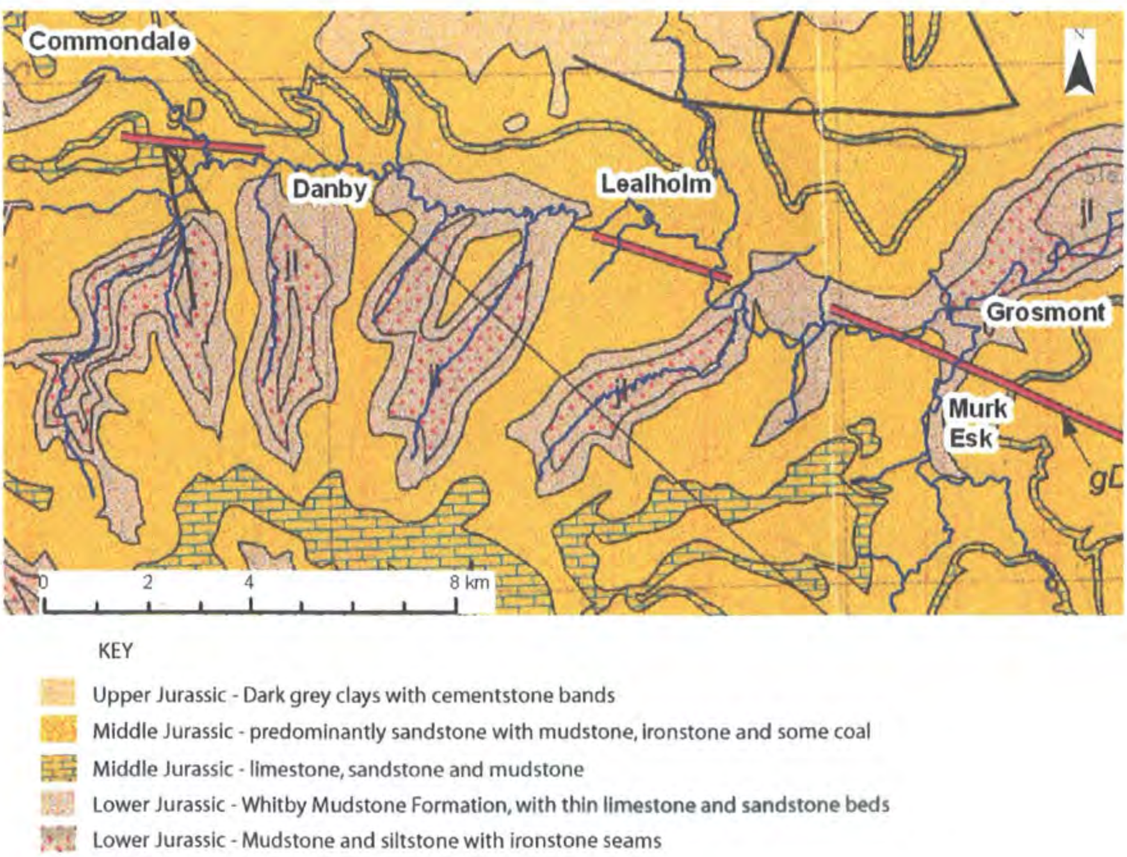


Figure 3.5: Solid geology of the Esk catchment (Source: British Geological Survey, 1995)

Owning to the unique glacial history (Section 3.2), the River Esk also exhibits interesting patterns of drift geology which overlie the solid geology. The majority of the main Esk incises sandy alluvium material; while the southern tributaries (e.g. Glaisdale Beck, Butter Beck and parts of Great Fryup Beck) flow over boulder clay drift geology. Since glacial material is comparatively softer and more easily eroded than solid geology, the spatial distribution of this drift geology will therefore influence the characteristics of the fine material transported in the Esk catchment.

3.5 Soils

The landscape hosts a variety of soils. In the valleys brown earths and stagnogleys, less than 0.8 m thick, dominate, whereas most of the Upper Esk is characterised by exposed lias rock cut by glaciers and peat bogs up to 2 m deep (Morley, 1997). This has implications with regards to the production of fine sediment as solid rock and peat deposits are relatively impermeable and generate more surface runoff; thus have the potential to transport larger sediment yields to the river network. Sands and gravels are also present in the headwaters, which allow a significantly large proportion of rainfall to be absorbed into the surface and could be characteristic of slower runoff rates. The erodibility of these different soil types and their spatial variability is a factor determining the production of fine sediment.

3.6 Climate

The mean annual precipitation in the Esk catchment is 822 mm (average recordings at Sleights gauging station 1961-1990) but this ranges within the catchment from 950 mm inland to 650 mm near the coast (EA, 2004). The catchment has mean annual temperatures of 9.5 ^{o}C ranging from a mean of 5 ^{o}C in January to 13 ^{o}C in August (Met Office, 2005). Mean flow measurement for the River Esk are 4.80 $m^3 s^{-1}$ (95% exceedence (Q95): 0.597 $m^3 s^{-1}$ 10% exceedance (Q10): 9.826 $m^3 s^{-1}$) (EA, 1997).

The Esk catchment has been observed to have large variations in storm rainfall events between seasons. Historical records show that past severe storm events have been more frequent between mid-summer and autumn. This is due to the influence of the relatively cold and dry continental polar air on north east England, which has limited capacity for moisture, and therefore is less likely to generate extreme rainfall (EA, 2005). In contrast to this, in the summer months the area is dominated by the warmer tropical continental air, which has a greater moisture capacity and ability to generate more intense storms (Figure 3.4).

3.7 Ecological significance

The lack of heavy industry along with relatively low intensity agriculture has resulted in the Esk having relatively high water quality and its fluvial habitat being highly diversified. For example, fish such as eels, graylings, brook lamprey, bullhead and minnows are found throughout the Esk (Gardiner, 1996). Moreover, the Esk is the only river in Yorkshire to support salmon and sea trout and as such represents an economically important fishery. Angling is important to the local economy providing rental incomes to riparian landowners, creating jobs in river management and providing business to the wider rural economy through demand for catering, accommodation and other services. It was estimated that in 1996 around 500 anglers fished in the Esk annually, bringing in a total of £45,000 in payments for club memberships and permits; thus the River Esk makes an important contribution to the biodiversity, economy and agriculture in the Esk valley (NYMNPA, 2001). Worryingly salmonid populations have been identified to be in dramatic decline in recent years, which has been attributed to the increasing suspended sediment levels in the Esk over the last decade (EA, 2004).

The Esk also supports five declining species identified by English Nature as 'Globally threatened/declining' including otter, water vole, kingfisher and dipper (NYMNPA, 2001). It is also one of the last English rivers which contain freshwater pearl mussels, which in recent years have also undergone dramatic decline. So much so, the Environment Agency is considering the drastic action of removing the few naturally remaining mussels so that they can be kept in captivity where artificial conditions can ensure their survival.

3.8 Land use history

Historically, deforestation has occurred in the Esk since the Bronze Age, but it was not until about 3500 BC when Neolithic settlers moved into the more fertile, flatter areas that intensive farming of the North York Moors began (Morley, 1997). By the mid-nineteenth century Upland parts of the catchment, including Upper Glaisdale, Westerdale and Upper Great Fryup Beck, were intensively cleared to make room for agricultural development. This started the degeneration of the thin soils which rapidly became deplete of nutrients and prone to erosion causing the inevitable collapse of Upland farming (Morley, 1997). With this removal of trees, competition plants, predominantly heather, spread over the depleted soils of the hills replacing the previously extensive deciduous woodland with wild, open moorland.

The current land use for the Upper Esk catchment is predominantly rural, mainly consisting of open areas of heather moorland managed for grouse (48 %) and agricultural land managed for sheep grazing (32 %). The rest of the land use is made up of woodland (10 %); arable (8 %); and built-up areas (2 %) (Figure 3.6).

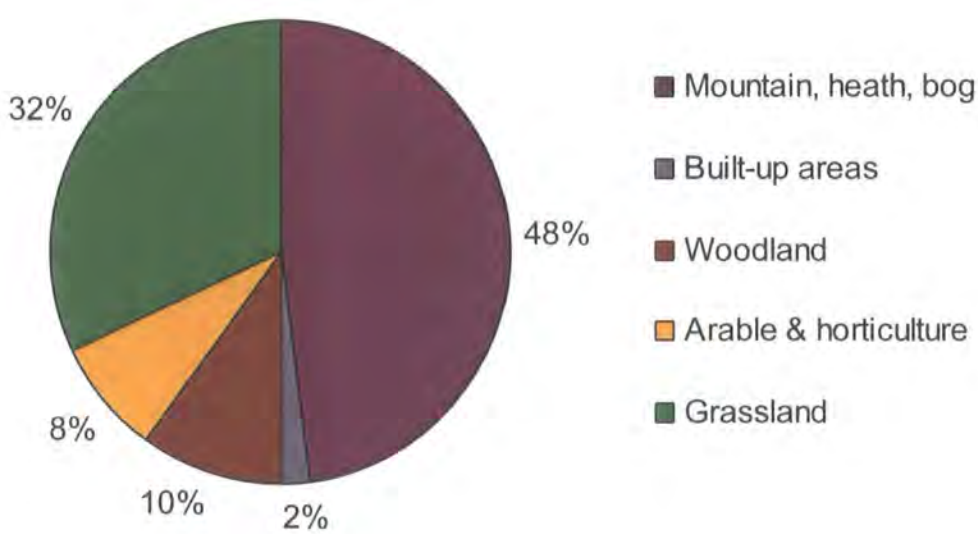


Figure 3.6: Land use of the River Esk catchment (2000) (Source: Land Cover Map, 2000)

In recent times, changes to land use management practices in the Esk include heather burning, installation of moorland grips (drainage), deforestation and most importantly, increased number of cattle and sheep. These are thought to have decreased the stability of the soil; hence accelerating erosion and deposition and resulting in flashier regimes with increased risk of flooding. The burning of peat and the removal of trees exposes thin peaty top soil to action of wind and rain where small streamlets or rills may erode down to the sandy subsoil. In time gullies can form from footpaths and forestry rides, causing an increase in sediment delivery to the river. This is of great concerning given the projected climate change increasing the magnitude of floods, increased population pressures placed on land use practices and increased tourism to predominantly rural areas. For example, visitor survey information in the early 1990's showed that 69 % of visitors to the North York Moors National Park visited the Esk Valley, totalling over 4.19 million day visits a year (NYMNPA, 2001).

Following the inception of the Forestry Commission after the First World War, there has been an increase in planting and managed coniferous forestry plantations in the River Esk catchment (e.g. Danby High Moor and Glaisdale Valley). This increase in tree cover provides both valuable habitat and soil stability to the area reducing the amount of fine sediment reaching the river system (Morley, 1997). Yet, forestry plantations can also actually increase fine sediment yields, especially in the initial stages of plantation, due to the disturbance of soil by heavy machinery and the creation of field drains (Stott, 1999).

3.9 Management initiatives in the Esk

Disturbing evidence to suggest recent increase in fine sediment associated with land use has been demonstrated by an on going projects funded by the Environment Agency. Of particular concern on the decreasing habitat numbers of salmonid and fresh water pearl mussels. Consequently this has highlighted the need for catchment initiatives targeting fine sediment delivery and deposition in the Esk catchment. Currently there are DEFRA funded agri-environmental schemes being conducted in the Esk catchment. For example adjacent to the River Esk there are five different Countryside Stewardship Awards (CSA) grants covering a total area of 78 hectares (EA, 2005). Woodland Grants have also implemented in the valles of Danby Beck and Great Fryup Beck. Parts of the Murk Esk have CSAs for preserving and improving field boundaries covering 36 hectares (Babtie Brown and Root, 2004).

'The River Esk Regeneration Programme' (RERP) was also been implemented from July 1997 to October 2001. The overall aim of the RERP was 'to protect, conserve and enhance the River Esk habitats for fish and other wildlife so as to increase the economic value of the river to the local rural community' (NYMNPA, 2001). The RERP was based on a range of grant-aided measures including capital river management works, a programme of native salmon fry stocking, monitoring of fish and training in fishery/river management. For example £13,067 was spent on bank side fencing, £17,640m on bank vegetation management and £734 m on tree planting schemes (NYMNPA, 2001).

To promote agri-environmental schemes amongst farmers and the local community, projects such as the 'North York Moors Farm and Rural Community Scheme' have also been adopted in the Esk catchment. The scheme examines the way current support mechanisms can be strengthened to deliver integrated rural development in the Uplands and operate within parishes (Babtie Brown and Root, 2004). However, catchment initiatives implemented in the Esk catchment have had varying degrees of success; most have been criticised for being poorly maintained after the initial setting up period and for having inadequate amounts of communication between catchment managers and farmers, landowners and the local community.

3.10 Representativeness of the River Esk

To summarise, the River Esk catchment represents an interesting Upland catchment study in which to examine spatial patterns of fine sediment flux, as a result of its unique glacial history, topography, drift and solid geology. This is especially so since fine sediment and associated land use practices in the Esk have already been identified as problematic to the aquatic habitats such as salmonids and freshwater pearl mussels. The small catchment area and rural location of the Esk means that it provides a suitable location to carry out an integrated catchment approach to monitor and record spatial patterns of suspended sediment characteristics. The data collected in this research study can then be used to add to the limited database concerning fine sediment dynamics in Upland catchments. Moreover, the River Esk also represents an important case study to inform Upland management studies and projects. However, given the individuality of this small catchment, it is questionable how much this study represents larger Upland catchment in general, and hence the amount to which the results of this research are transferable to other upland catchment.

Chapter Four: METHODOLOGY

4.1 Overview

The main methods used in research can be split into three categories;

1. Collection of field data (4.2) including: spatial suspended sediment sampling (4.2.1); 'gulp' sampling (4.2.2); river monitoring (4.2.3); channel mapping (4.2.4); and sediment source sampling (4.2.5).
2. Laboratory measurements (4.3) including: dry sediment yields (4.3.1); suspended sediment concentrations (4.3.2); particle size distribution (4.3.3); metals (4.3.4); magnetic susceptibility (4.3.5); and sediment colour (4.3.6).
3. GIS analysis (4.4).

These methods are described in this chapter.

4.2 Collection of field data

4.2.1 Spatial suspended sediment sampling

To assess the relationship between spatial variations in fine sediment supply and land use in the River Esk, a representative spatial coverage of sampling sites was achieved using a network of 17 TIMS sampling sites strategically deployed throughout the Upper Esk catchment. Locations of these TIMS samplers (Figure 4.1) were selected using information provided from preliminary reports (Bracken and Warburton, 2005) to provide a good coverage of potential suspended sediment transfer throughout the main Esk and its dominant tributaries.

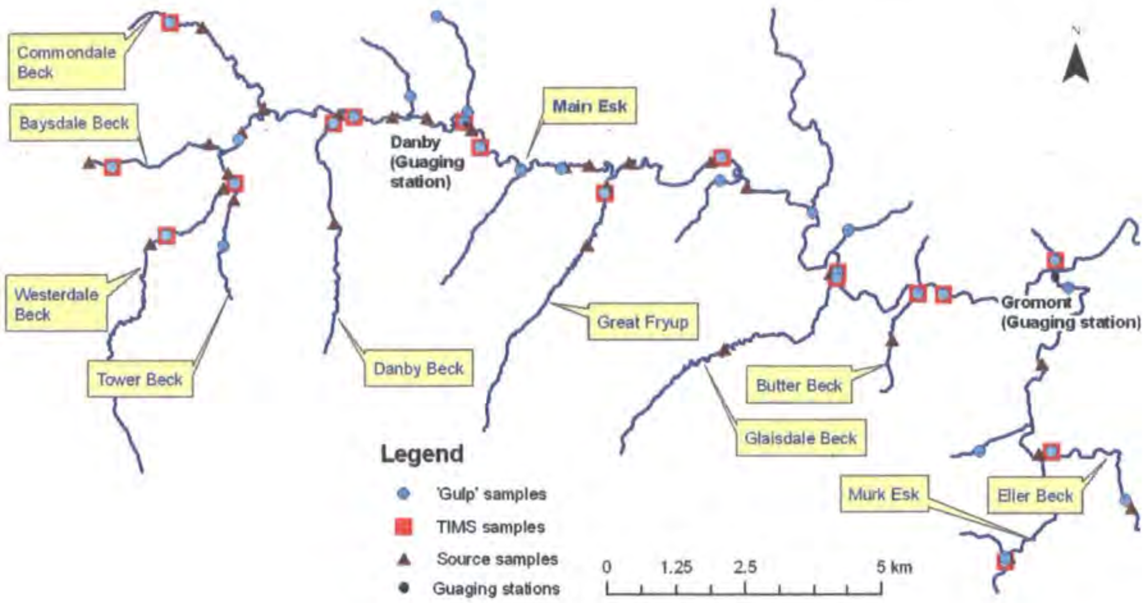
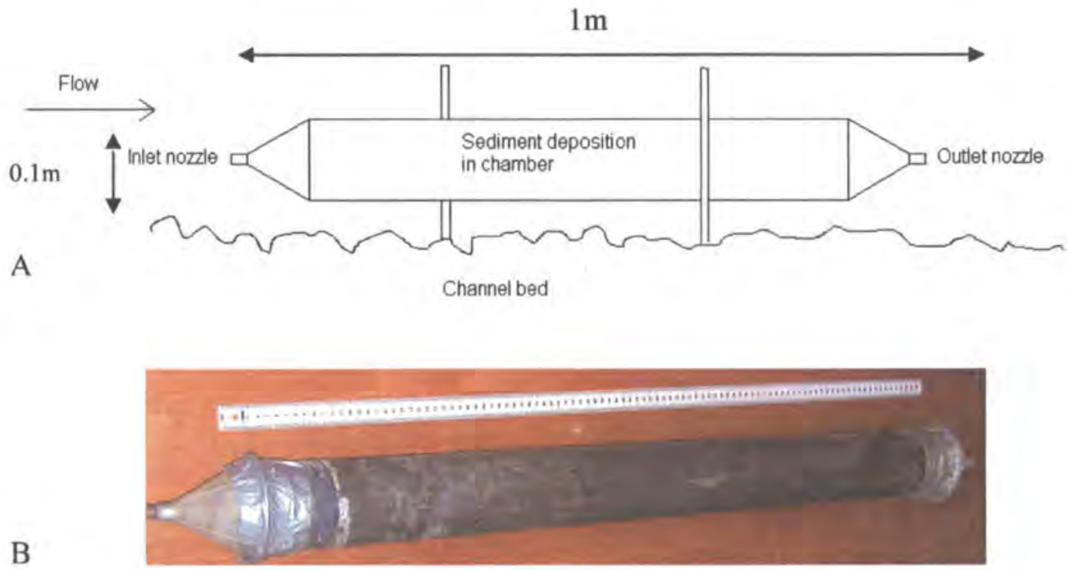


Figure 4.1: Spatial distribution of TIMS, 'gulp' sampling, sediment source sampling and river gauging sites in the River Esk catchment

TIMS are designed to continuously sample suspended sediment during their period of deployment and have the ability to collect *in situ* samples. The TIMS consists of 1 m length plastic pipe of 0.1 m diameter sealed with plastic caps, threaded with 8 mm internal diameter hosepipe inlet and outlet tubing. Funnels with the inlet/outlet tubing threaded through were placed at either end creating a streamlined intake and outflow so to decrease the hydrodynamic disturbance created by the sampler. The samplers were secured approximately 0.1 m above the stream bed and held in place using two 1 m long metal rods and cable ties (Figure 4.2). The sampling principle behind the mechanism of the TIMS is that water flows through the restricted inlet pipe, enters the larger chamber and the velocity is significantly decreased causing the sediment to settle out and be deposited in the sampler body. Sediment free water is then discharged through the exhaust tube at the rear (Figure 4.2).

TIMS have the advantage of allowing suspended sediment flux to be measured continuously, provide estimates of total storm yields and can be distributed throughout the catchment to capture the spatial variability of suspended sediment transfer. TIMS samplers are also economical, easy to construct, maintain and empty and can be deployed in most channels (providing the river levels are not too high), allowing bulk samples of fine sediment to accumulate without the need to collect large volumes of river water (Russell *et al.*, 2000). However, TIMS emptying frequencies can be compromised due to accessibility problems and high river stages causing variable deployment times. Floating debris can also block the inlet tube, decreasing the validity of the spatial and temporal comparisons made (Phillips *et al.*, 2000).



A

B

Figure 4.2: A) Diagram and A) Photo of a TIMS (Phillips *et al.*, 2000)

The samplers were installed from December 2005 to June 2006 to give a detailed winter to spring seasonal comparison so to establish the temporal effect on fine sediment transfers. A fixed four week emptying frequency was used so that the collected sediment fluxes were comparable and so the magnitude and frequency of the storms during each sampling period could be assessed.

4.2.2 Storm 'gulp' samples

Further information on the influence of storms on the spatial pattern of suspended sediment transfers was established by collecting spatial storm 'gulp' samples during large floods in November (9/11/05) and May (20/05/06) from the main 18 sampling sites and 20 additional locations (Figure 4.1). The data collected provides a detailed picture of the effect of large floods on suspended sediment concentrations, as well as providing an indication of the suspended sediment dynamics in the watercourses not monitored by TIMS.

The spatial gulp samples were collected using a 3 m wooden rod with a pre-rinsed 500 ml wide necked bottle attached to the end. This was placed into the river facing into the flow, allowed to be filled, then removed and emptied into a clean, labelled 500 ml wide necked bottle. Samples were taken as far from the banks as possible so to avoid any local bank erosion biasing the results.

4.2.3 River monitoring

Two field monitoring stations were installed in the River Esk at Danby (NZ 717083) and Grosmont (NZ 826050) (Figure 4.1, 4.3A and B). The sites are approximately 14 km apart on the main River Esk channel, have differing catchment areas (90 km^2 and 210 km^2 respectively) and have different source areas for runoff and sediment supply, making them excellent location to gauge and compared changing river characteristics downstream on the main Esk.

Figure 4.3: A) Location of gauging station at Danby and B) Grosmont

These sites were set up to monitor rainfall (using a tipping bucket rain gauge), stage (using a pressure transducer), temperature (using a thermistor) and turbidity (using a turbidity nepholmetric probe) (Table 4.1; Figure 4.4). Using Campbell (CR10X) data loggers, measurements from each sensor were scanned every 3 minutes and recorded every 15 minutes, over a six month period from December 2005 to June 2006. This provided a detailed temporal record of river flow characteristics which can be used when analysing the data collected from the TIMS.

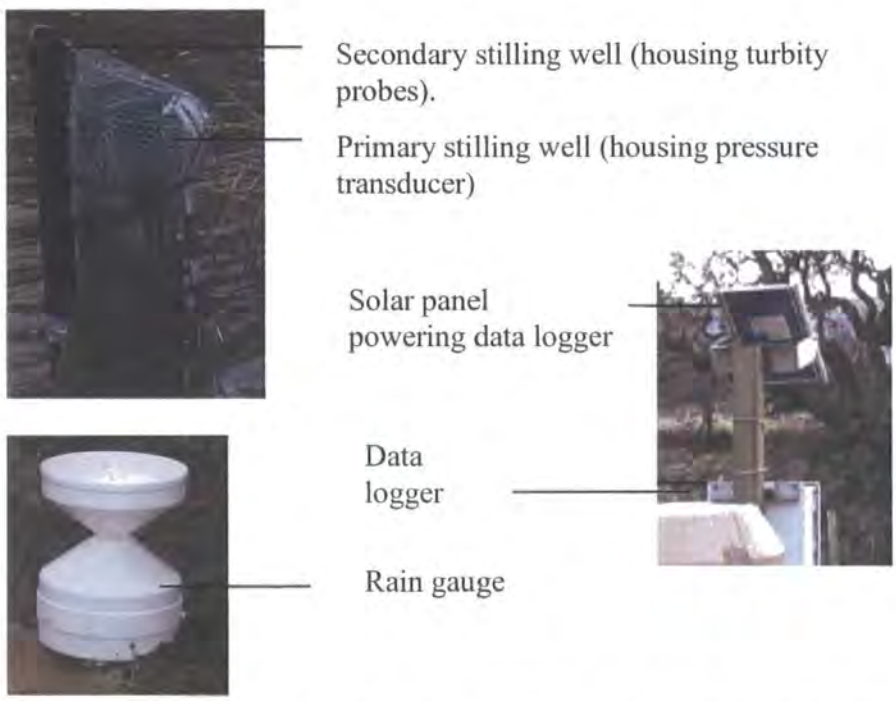


Figure 4.4: Setup up of equipment at the gauging stations, showing the main components

Table 4.1: Description of equipment installed at Danby and Grosmont

Equipment	Danby	Grosmont
Logger	Campell CR10X	Campell CR10X
Stage gauge	Druck PDCR 1830	Druck PDCR 1830
Rainfall	Tipping bucket ARG100	Tipping bucket ARG100
Temperature	Thermistor Probe 107	Thermistor Probe 107
Turbidity	McVan 390G	McVan 390G
Water sampler	Sigma 900 max	Sigma 900

4.2.4 Channel mapping

Channel bank characteristics of the main Esk, between Castleton and Grosmont, and its main tributaries were mapped (Figure 4.5; Table 4.2) by walking the channel banks and recording channel characteristics of both banks using standard field worksheets (Table 4.3). Although the majority of the catchment was mapped, parts were not due to problems of inaccessibility and land access.

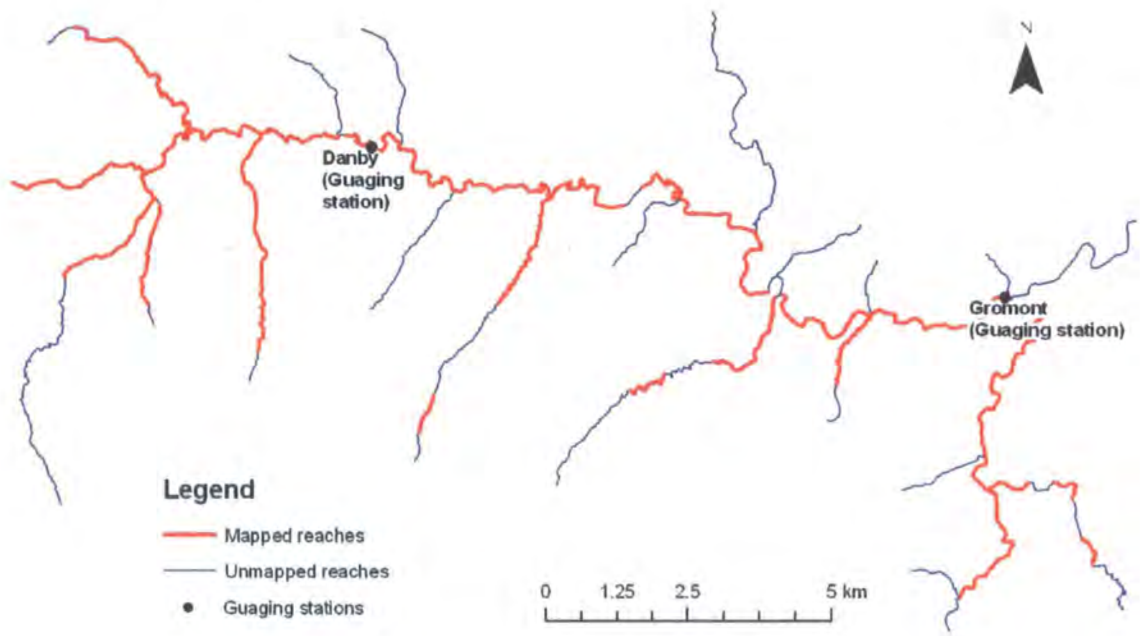


Figure 4.5: Spatial extent of channel mapping in the Esk catchment

Table 4.2: Extent of watercourses mapped in the Esk catchment

Watercourse	Distance mapped (km)	Watercourse	Distance mapped (km)
Commondale Beck	3.76	Butter Beck	1.48
Baysdale Beck	4.05	Murk Esk	7.79
Westerdale Beck	3.02	Eller Beck	2.27
Tower Beck	1.92	Start of Esk to Danby	6.35
Danby Beck	4.29	Esk at Danby to Lealholm	9.26
Great Fryup Beck	3.51	Esk at Lealholm to Glaisdale	3.56
Glaisdale Beck	3.34	Esk at Glaisdale to Grosmont	5.85
		TOTAL DISTANCE	60.63

Table 4.3: Left Bank (LB) attributes and codes used in the channel reconnaissance (repeated in each reach for right bank attributes (RB))

Attribute Name	Attribute Description	Code description
REACH		
Flow	High/medium/low	
LB_height	Bank full height (m)	
Width	Bank full width (m)	
LB%_woody	Percentage cover of trees (%)	
LB%_grassy	Percentage non-woody cover (%)	
LBLand_use	Dominant land use	A (Arable), P (Pasture), W (Woodland), G (Gardens/Parks), R (Roads/Railways), M (Moorland), O (Other)
LB bank_mat	Dominant bank material	F (Fines), S (Sand), G (Gravel), B (Boulders), A (Artificial), Ob (Obscured), O (Other)
LB status	Dominant condition of bank	E (Eroding), D (Depositing), S (Stable)
LB erode_type	Dominant erosion process	E1 (Subariel - rain splash or freeze thaw), E2 (Fluvial - entrainment of bank by river), E3 (Geotechnical - internal collapse), E4 (Burrowing), E5 (Poaching), E6 (Tree scour -caused by flow deflected round trees), E7 (Footpath), E8 (Soil piping)
LB eroext	Extent of erosion	0 (No significant bank erosion) 1 2 3 4 (Very extensive bank erosion)
Bedmat	Dominant bed material	S (Sand), G (Gravel), B (Boulders), O (Obscured)
% sand	% area of bed covered by sand	
Bedmorph	Morphology of sand on bed	Du (Dunes), R (Ripples), D (Drapes), O (Obscured)
Bedcover	Dominant bed cover	Veg (Vegetation), Peri (Periphyton), None (None), O (Obscured)
MIDCHANNEL		
Type	Type of mid channel feature	VM (vegetated mid-channel bar), MI (Mature island), PB (Point bar), SB (Side bar), BB (Braided bars)
Area	Area of mid-channel feature	m^2
INPUTS	Type of point input	TRIB (tributary), DRAIN (pipe/drain), POACH (animal poaching), OTHER

For the purposes of mapping, geomorphically similar reaches were defined. A new reach was surveyed each time a significant change occurred in the channel geomorphology (e.g. a change in channel bank material or dominant erosion type) allowing the detail in channel variability to be mapped. To assess the extent to which the catchment was connected to the hillslope, the occurrence of catchment inputs (drains, tributaries and saturated runoff) for each geomorphically defined reach were also recorded (Table 4.3).

Standard recording sheets were formatted into a handheld Leica GS20 GPS data recorder; a Garmin eTrex handheld GPS with printed standard recording worksheets were used where the Lecia GS20 GPS could not get a good signal due to high tree coverage and steep valley slopes. This allowed channel attributes, such as bank height (m), dominant bank material and erosion extent, to be quickly and easily recorded creating a database of channel characteristics that covering a total of 61 km of river reaches in the Esk catchment (Table 4.2). These GPS reference observations were plotted into ARCview (Section 4.4) creating a fluvial geomorphological sediment audit of the river Esk catchment. The data collected here will confirm spatial patterns of fine sediment movement identified using the TIMS samplers and provide information for identifying significant sediment source areas in the catchment (Section 4.2.5).

Limiting the validity of this channel mapping methodology is that some of the classifications are necessarily crude and subjective (e.g. erosion extent); some of the categories were highly variable depending on the weather (catchment inputs); and season (vegetation cover). This was minimized using by carrying out most of the fieldwork within one week.

4.2.5 Source sampling

Sediment source samples were collected to compare with the mass bulk suspended sediment samples collected in the TIMS with the purpose of identifying dominant sediment sources within the cathcment. Channel bank and catchment source samples were collected using a clean metal trowel and labelled plastic bags from potential areas of suspended sediment inputs (e.g. sites of significant bank erosion). These were identified while mapping the catchment characteristics; the locations of which are shown in Figure 4.1. To gain a spatial overview of channel bank source areas, two samples were collected from each of the main tributaries and a further ten samples were collected from the Main Esk.

4.3 Laboratory Analysis

The laboratory methods are summarised below:

Table 4.4: Summary laboratory techniques used in the investigation and relevant sections in this chapter

Type of Sample	Laboratory Technique					
	Sediment yield	**SSC***	**PSD****	**Heavy metals**	**Magnetic susceptibility**	**Colour analysis**
TIMS	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6
Gulp sample		4.3.2				4.3.6
Sediment source sample			4.3.3	4.3.4	4.3.5	
Flood sample		4.3.2				

(* Suspended sediment concentration; ** Particle size distribution).

4.3.1 Dry sediment yield

The dry sediment weights of the samples were obtained using the following standard procedure:

1. The large 5 L plastic bottles containing the wet sample emptied from the TIMS were immediately refrigerated in the labs at 3 °C to stop algal growth.
2. The bulk samples were then emptied into the 8 L plastic, labelled, pre-rinsed settling containers and any remaining water was rinsed out using distilled water.
3. Settling containers were angled so sediment would collect in one corner of the tanks.
4. The containers were then covered and left for 48 hours for the sediment to settle.
5. Excess water was then siphoned off and the volume of water drawn off measured.
6. Part of this siphoned water was also filtrated (Steps 4-10 in section 4.3.2) to calculate the suspended sediment concentration.
7. Labelled beakers were weighed to an accuracy of 0.001 g.
8. The sediment remaining in the containers were then poured into labelled glass beakers. The remaining sediment was flushed out with distilled water.

9. The sediment in the beaker was then dried out in the oven at 35 °C (a lower temperature than standard is used here so that the magnetic properties of the sediment are not destroyed (Section 4.3.5).
10. Once the sediment in the beaker has settled excess water can also be pipetted off to aid the rate of evaporation.
11. The beaker and dried sample are reweighed to an accuracy of 0.001 g.
12. The total sediment mass of the sample was then calculated by adding the dry weight of the sediment to the sediment mass calculated from the concentration recorded in the excess water.

4.3.2 Suspended sediment concentration

Suspended sediment concentrations were determined using a vacuum filtration method using the following standard procedure:

1. Whatman GF/C 47 mm glass microfibre filter papers (which retains particles >1.2μm) were dried out by placing them in the ovens at 105 °C for 24 hours.
2. They were placed into numbered dishes and weighed to an accuracy of 0.0001 g.
3. The volume of the water sample was measured using a measuring cylinder.
4. This water sample was poured on to its associated filter paper and filtered under vacuum.
5. The measuring cylinder and sample bottle were rinsed with distilled water to flush out the remaining sediment.
6. Once all the water was filtered through, the sides of the filter holder were rinsed with distilled water to wash all the sediment onto the filter paper.
7. Using tweezers, the filter paper was carefully removed and placed back into its filter dish.
8. Steps 3-7 were then repeated till all the water samples had been filtered.
9. All the dishes were then placed into the oven to dry at 105 °C for 24 hours.
10. The dishes were then placed in desiccators to cool and then reweighed.

These recorded volumes and masses were used to calculate the suspended sediment concentration:

$$SSC = (W_2 - W_1)/V \qquad (4.1)$$

Where:

SSC	=	Suspended sediment concentration
W_1	=	Weight of filter paper and dish
W_2	=	Weight of dried sediment, filter paper and dish
V	=	Volume of filtered water sample

4.3.3 Particle size distribution

The particle size distribution of both the suspended sediment and source samples were determined using the following standard procedure:

1. The dried sediment taken out of the oven at 35 °C (Section 4.3.1) and was sieved through a 2 mm sieve.
2. The fraction of the sample larger than 2 mm was weighed to an accuracy of 0.001g.
3. The fraction finer that 2 mm was then put through a riffle box and a representative 0.5 g (approx) sub sample was taken.
4. This was prepared for analysis first by adding 20 ml hydrogen peroxide to remove organic material, then by leaving in sodium hexametaphosphate for 24 hours to deflocculate the particles.
5. These samples were then decanted, refilled with distilled water and centrifuged twice.
6. Samples were then analysed using a Coulter laser granulometer (LS230) to determine particle size (Range of analysis 0.04 μm to 2000 μm).
7. Two measurement runs were made for each sample, unless the runs did not show a close match, in which case additional runs were made.
8. These results can be analysed by plotting them into Gradistat which allows rapid analysis of grain size statistics such as the median (D_{50}) (Blott and Pye, 2001).

4.3.4 Heavy Metals

Total heavy metal analysis (Table 4.5) was determined for both the mass flux samples and the sediment source samples allowing metal concentrations to be compared and dominant sources identified.

Table 4.5: Heavy metals analysed for both suspended TIMS and sediment source samples

Metal symbol	Metal name	Metal symbol	Metal name	Metal symbol	Metal name
Be	Berylium	Mn	Manganese	Mo	Molybdenum
B	Boron	Co	Cobalt	Ag	Silver
Al	Aluminium	Cu	Copper	Sb	Antimony
Ti	Titanium	Zn	Zinc	Ba	Barium
V	Vandium	As	Arsenic	TI	Thallium
Cr	Chromium	Se	Selenium	Pb	Lead
Fe	Iron	Sr	Strontium	Bi	Bismuth

Heavy metal content was determined using the EPA 3052X standard digestion method outline below:

1. Once the mass flux sample had been dried in the oven (35 °C) (Section 4.3.1), the sample was frozen at -80 °C (24 hours), in a freeze dryer (24 hours) to completely remove any trace of water left in the sample.
2. The samples were then broken up in a ball milled for four minutes.
3. A 200-250 mg sub-sample was then weighed
4. 5 ml of H_2O_2 and 2 ml of H_2O_2 were added and left to stand until the reaction had stabilised.
5. Then 2 ml of HCl and 9 ml of HNO_3 were added followed by 3 ml of HCl.
6. The sample was then sealed in the microwave system (MARS5CEM) and set for a 15 minute digestion followed by a 10 minute standing period.
7. The samples were then filtered, made up to 100mls and analysed using an ELAN DRC plus ICP mass spectrometer for metal concentrations.
8. Results were reported to an accuracy of 3 significant figures.

4.3.5 Magnetic susceptibility

Magnetic susceptibility is a measure of the ease with which a material can be magnetized (Thompson and Oldfield, 1986) and can be used as a diagnostic property to fingerprint suspended sediment sources (Walden *et al.*, 1997). It provides a measure of the ferromagnetic mineral component of a sample, which includes minerals such as magnetite (Dearing, 1994). If there is a low concentration of ferromagnetic minerals, paramagnetic minerals such as siderite and pyrite can significantly contribute to total susceptibility (Thompson and Oldfield, 1986).

Low frequency susceptibility (X_{lf}) is a measure of the total ferromagnetic component of a sample. High frequency susceptibility (X_{hf}) is a measure of the concentration of ferromagnetic grains larger than 0.035 µm (Evans and Heller, 2003) and both can be measured using a Bartington MS2 Magnetic Susceptibility Meter. The standard method used is outlined below (Dearing, 1994):

1. The sample mass of an empty, labelled 10 cc sample pots was recorded to an accuracy of 0.0001g
2. These 10 cc sample pots were then filled with the sample (which had been previously dried (30 °C), frozen (-80 °C), air dried and ball milled) and reweighed to an accuracy of 0.0001g

3. The susceptibility of the sample measure at both low (0.465 Hz) and high (4.65 Hz) frequencies
4. A calibration standard 361 csg reading was taken between low and high frequency settings
5. Six consecutive readings were taken per sample, a blank reading (empty pot), 4 readings with the sample in the meter (rotating the pot quarterly between readings), followed by another blank reading
6. Results are expressed in SI units (10^{-8} (m^3 kg^{-8})).

Each reading was initially converted into to low and high volume specific magnetic susceptibilities (X_{vollf} and X_{volhf} respectively) using equation 4.2.

$$X_{vol} = ((R_1 + R_2 + R_3 + R_4)/4)) - ((B_1 + B_2)/2) \qquad (4.2)$$

Where: X_{vol} = volume specific magnetic susceptibility

R = reading of the sample

B = reading of blank pot

Mass specific magnetic susceptibility for low and high frequencies (X_{lf} and X_{hf} respectively) can also be calculated to account for the different sample masses used using equation 4.3.

$$X = X_{vol} / density \qquad (4.3)$$

Where: X = mass specific magnetic susceptibility

X_{vol} = volume specific magnetic susceptibility

Density = $\dfrac{\text{mass of sample (g)}}{\text{volume (10 cm}^3\text{)}}$

Lastly, frequency dependent susceptibility ($X_{fd\%}$) can be calculated from the low and high frequency mass specific susceptibilities (Equation 4.4), and provides a measure of the concentration of ferromagnetic grains smaller than 0.035 μm relative to the total number of ferromagnetic grains (Dearing *et al.*, 1996). A high $X_{fd\%}$ represents the presence of small ferromagnetic grains formed during pedogneic processes.

$$X_{fd\%} = 100(X_{lf} - X_{hf}) / X_{lf} \qquad (4.4)$$

Where: $X_{fd\%}$ = Frequency dependent susceptibility

X_{lf} = Low frequency mass specific susceptibility

X_{hf} = High frequency mass specific susceptibility

4.3.6 Sediment Colour

Sediment colour has noted to be spatially highly variable in the Esk catchment (Bracken and Warburton, 2005) and could reflect the contribution of different source areas; hence, sediment colour has been analyzed in this project. The sediment colour of dry filter papers (collected from the TIMS and 'gulp' samples) was determined using the Munsell® Soil Colour Charts (1992). In using colour charts, accurate comparisons can be obtained by holding the sample directly behind the apertures separating the closest matching colour chip. The Munsell® Soil Colour Chart was used to describe the hue (its colour in relation to red, yellow, green, blue and purple) value (indicates lightness) and chroma (strength) to create a H V/C colour notation.

Errors can occur when using the Munsell Soil Color Chart, such as distinguishing between colours that fall in between colour categories on the chart. Also, the ability to sense color differences and individual perceptions of colour is highly variable. However this method was preferred over a method of images scanning of the filter paper, as the resolution of the scanner was not high enough to depict the variability of the colour on the filter papers. The Munsell hue, value and chroma (H V/C) notations made for the different filter papers were then converted to red green blue values using Munsell Conversion Software V6.5.17 which can then be graphically presented and analyzed.

4.4 GIS analysis

The GPS reference channel attribute observations created while mapping the catchment (Section 4.2.4) can be plotted into ArcGIS to create a GIS database of catchment characteristics. This was done by copying all the channel attributes into an attribute table in ARCmap and assigning each surveyed reach an ID number. These surveyed reaches can then be displayed spatially on a River Esk base map whereby each line displayed is linked to its associated set of channel characteristics in the attribute table. By highlighting certain attributes (e.g. bank height over 2 m or erosion extent over 3) and assigning these highlights colours, shapefiles can be created which spatially illustrates the different categories of attribute characteristics. This therefore produces a summary map for each channel bank characteristics, where the colour of line on the reach indicates the sub-category for each mapped attribute (see example of shapefile Figure 4.6).

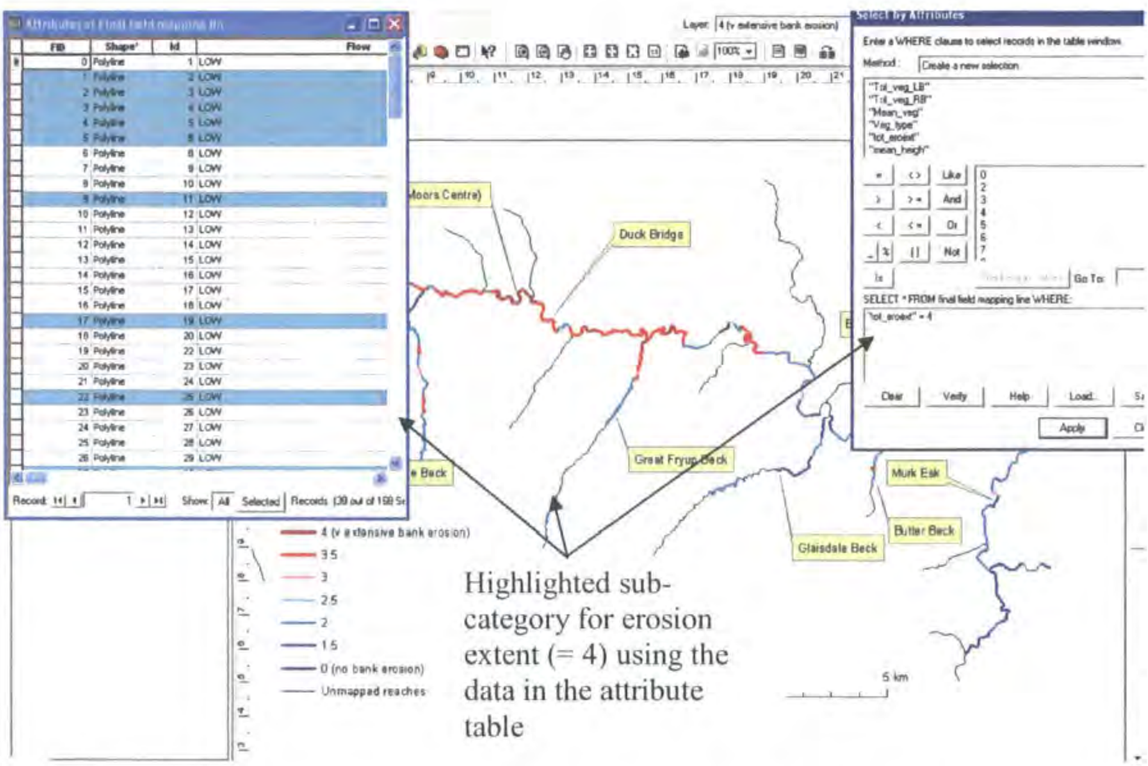


Figure 4.6: Example of creating a shapefile for erosion extent in ARCmap by highlighting certain sub-categories from the attribute table on a River Esk map.

These attribute maps allow a detailed understanding of the spatial and temporal variability in suspended sediment characteristics and channel attributes in the River Esk catchment. In particular, they can be used to identify sediment source characteristics and changes in channel form and process in the main tributaries and down the main Esk. This aids source area identification and the ability to link problematic 'hotspots' in suspended sediment to land management practices in the catchment. Using GIS software, it is possible to combine these channel characteristics with other spatial coverages, such as elevation, slope and geology, to elucidate some of the catchment controls on spatial patterns of sediment flux.

4.5 Chapter summary

In summary, this chapter outlines the main methodological procedures used in the field and laboratory. The dry sediment weight and the suspended sediment concentration are measured using a spatially integrated network of 17 TIMS and spatial storm 'gulp' sampling. The data collected provides a spatial coverage of fine sediment transfers in the Esk catchment. River monitoring is used to assess the temporal importance of storm magnitude and frequency on these spatial patterns. To confirm spatial patterns in sediment dynamics, channel reconnaissance can be used to infer the significant source areas of fine sediment by creating a fine sediment audit of the catchment. Sediment properties of the TIMS samples can combined with the sediment source samples to identify dominant sources within the catchment. These results, in combination with geology and elevation information, can then be combined using GIS to spatially analyse catchment characteristics.

Chapter Five: SPATIAL AND TEMPORAL PATTERNS OF FINE SEDIMENT TRANSFER

5.1 Overview

The identification of areas of fine sediment flux in the Esk catchment is not only necessary for the detection of dominant sediment sources, but will prove essential to the implementation of management strategies to alleviate high levels of sedimentation. It is also important that temporal trends in fine sediment transfer are considered to provide an understanding of how sediment movement in the catchment responds seasonally and with changing flow conditions.

This chapter examines spatial patterns of sediment flux in the Esk catchment using the bulk sediment yields retained in the TIMS samplers (Sections 5.2.2 – 5.2.5). Secondly, to provide an indication of sediment transfer in the catchment during high flows, suspended sediment concentrations collected from storm 'gulp' samples are examined (Section 5.3). Finally, longer term temporal trends are considered to elucidate the seasonal (Section 5.4.1) and high flow effect on these spatial patterns of fine sediment supply (Section 5.4.2).

5.2 Spatial patterns of sediment flux

5.2.1 Sediment flux

To assess the spatial pattern in sediment transfer, total fluxes obtained from the TIMS samplers were initially standardised by dividing the dry sediment mass collected by the number of days the sampler was deployed in each sampling period; giving a sediment flux in grams per day (g d^{-1}). This provides an estimation of the amount of sediment passing through the sampler over the sampling period at a given cross section. The box plots (Figure 5.1) show Egton Bridge, Butter Beck and Duck Bridge to have the highest sediment flux (3.55 g d^{-1}; 2.88 g d^{-1}; 2.86 g d^{-1} respectively); whereas Westerdale Beck, Baysdale Beck and Six Arch Bridge were found to have the lowest (0.42 g d^{-1}; 0.78 g d^{-1}; 0.80 g d^{-1} respectively). Figure 5.1 also highlights that with increasing sediment flux, the variability between sampling periods also increases, suggesting that locations with higher flux also have increasingly variable source areas and flow paths.

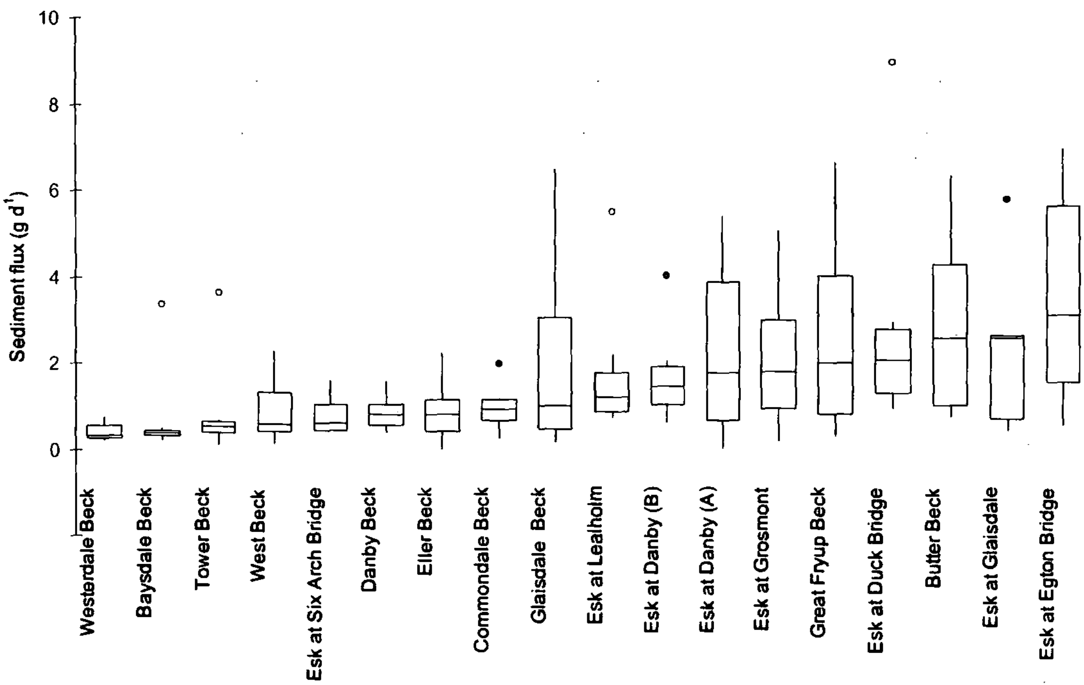


Figure 5.1: Box plots of sediment flux collected from TIMS (g d^{-1}) ordered by median sediment yield (n = 7 sampling periods, December 2005 – June 2006)

When these sediment fluxes retained from the TIMS are compared to the specific catchment area draining into each TIMS, a weak positive relationship is observed (R^2 = 0.23). This would be expected given the increase in contributing catchment area downstream (Crosby and DeBoer, 1995). The weakness of this trend could be a result of bank failures contributing a significant amount of fine sediment inputs further upstream, causing higher sediment yields in comparison to drainage basin area (Figure 5.2).

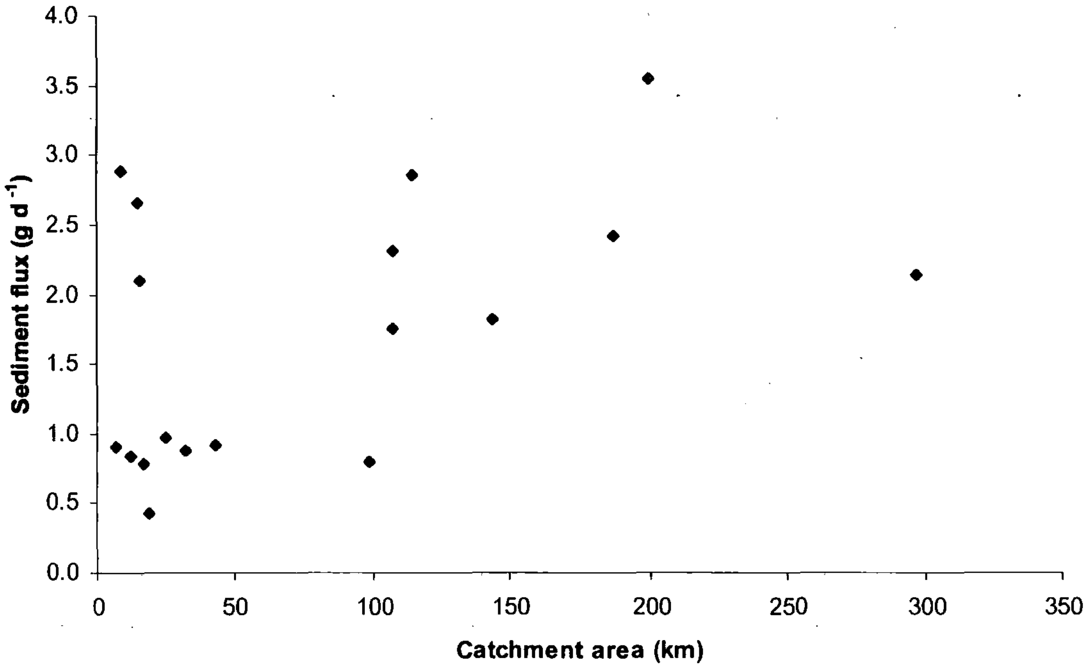


Figure 5.2: Comparison of mean sediment flux (g d^{-1}) retained from the TIMS and catchment area (km) ($R^2 = 0.23$).

This spatial distribution in sediment flux can be examined in more detail using the mean sediment fluxes (g d^{-1}), collected over the seven sampling periods, to create proportional circles where the diameter of the circle indicates the largest mean sediment flux observed at each site. These proportional circles can then be overlaid onto the river line map for the Esk to illustrate the spatial context (Figure 5.3).

The spatial distribution in sediment flux highlights two main 'hotspots' in sediment transfer (red transparent circles in Figure 5.3); the first being the section of the main Esk from Danby (Moors Centre) to Duck Bridge; the second from Glaisdale to Egton Bridge, also on the main Esk. The tributaries Great Fryup Beck, Glaisdale Beck and Butter Beck are also highlighted as having high sediment fluxes. The tributaries draining into the Upper Esk above Danby, such as Westerdale Beck, Baysdale Beck, Commondale Beck and Tower Beck, have comparatively low sediment fluxes; as well as the Murk Esk and Eller Beck that enter the main Esk at Grosmont. This suggests a downstream trend of increasing sediment flux which is commonly found in river catchments due to increasing channel size and capacity, and hence the ability to transfer sediment downstream.

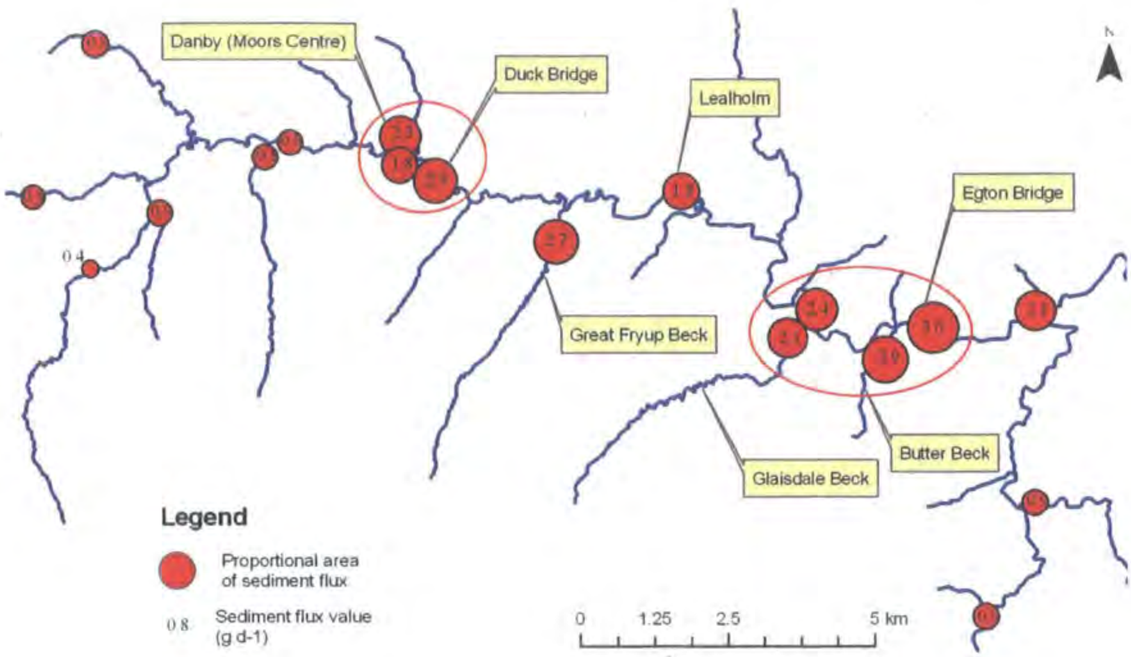


Figure 5.3: Mean sediment flux (g d^{-1}) collected from the TIMS (n = 7 sampling periods, December 2005 – June 2006) (Red transparent circles indication the main 'hotspots' in sediment supply)

5.2.2 Weighted sediment flux

Looking at the sampler sediment flux alone does not create an accurate appreciation of sediment transfer since it does not account for the variation in cross sectional area at the different TIMS sampling points in the catchment. This is an important consideration because the ratio of the inlet tube area on the TIMS relative to the channel cross sectional area will vary in the river system. For example, in smaller tributaries the size of the inlet tube relative to the cross sectional area is larger and therefore has the capacity to capture proportionally more of the total sediment flux. Thus, to provide a more accurate representation of spatial patterns in sediment delivery and transport, sediment flux can be weighted according to the site specific cross sectional area at the TIMS location, to give a site specific weighted sediment flux. Calculating sediment flux in this manner will also give an indication of the significant tributaries and sections of the main Esk in terms of the amount of fine sediment transported and supplied to certain locations.

However, this method raises several issues when trying to estimate cross sectional area at ungauged sites. Two methods were used; firstly in the field the present flow levels were used as a base level to measure the width and depth of the channel at the TIMS site: Secondly bankfull widths and depths were estimated at each site using local indicators such as bank morphology, vegetation and trash lines. There are advantages and disadvantages to both methods. Firstly measuring channel dimensions based on the level of the flow are easier to carry out, yet due to the variability of flow, do not provide accurate, comparable cross sectional areas on a catchment scale. Secondly, bankfull measurements provide more comparable estimates but are harder and more subjective to identify accurately in the field and are more prone to large errors. After comparing the two methods it was decided that bankfull channel dimension were more suitable for calculating weighted sediment fluxes because it allowed greater consistency between sampling sites; hence bankfull channel capacities will be used to weight the sediment fluxes obtained from the TIMS samples in this in this thesis.

Weighted sediment fluxes were calculated by multiplying the bankfull channel capacity (m^2) by the total mass of sediment collected in the TIMS for each sampling period (g) which was then divided by the number of days the sampler was deployed (d), providing a weighted sediment flux (g d^{-1}) (summarised in Table 5.1).

$$\text{Weighted sediment flux} = \frac{A_b f \times M}{d} \qquad (5.1)$$

Where:

$A_b f$	=	bankfull channel capacity
M	=	total sampler yield
D	=	number of days that the sampler was deployed

Examining the box plots (Figure 5.4) and the proportional circle plot (Figure 5.5), spatial patterns in weighted sediment fluxes highlight the two 'hotspots' in sediment supply from Danby (Moors Centre) to Duck Bridge and from Glaisdale to Egton Bridge, as identified by the sediment flux plots (Figure 5.3). The weighted sediment fluxes also emphasise the importance of fine sediment supply at Grosmont, Egton Bridge and Glaisdale; yet lessened the significance of the tributaries. This suggests that since sampler sediment flux (unweighted) does not account for the spatial variability in channel dimensions and hence the capacity of a certain cross section in transporting sediment, areas of sediment supply in Figure 5.3 are under or over estimated depending on bankfull cross sectional areas. This subsequently highlights a significant limitation in using an unweighted sediment flux, in comparison to weighted sediment flux, to examine sediment transfer in a catchment. Butter Beck can be highlighted as an anomaly as despite its relatively small cross sectional area (10.75 m^2), it is still highlighted by weighted sediment fluxes as being important in terms of supplying the main Esk with sediment.

Table 5.1: Catchment area, bankfull channel capacity, weighted sediment flux and standard deviation for each TIMS sampling site

TIMS sampling site	Catchment area (km^2)	Bankfull channel capacity (m^2)	Mean weighted sediment flux (g d^{-1})	Standard deviation
Tower Beck	6.71	1.76	6.71	0.81
Butter Beck	8.79	10.75	8.79	9.24
Danby Beck	12.06	7.68	12.06	1.22
Great Fryup Beck	14.47	3.97	14.47	3.57
Glaisdale Beck	15.38	17.79	15.38	16.80
Baysdale Beck	17.10	3.04	17.10	1.31
Westerdale Beck	18.57	6.35	18.57	0.61
Commondale Beck	25.01	4.44	25.01	0.91
Eller Beck	31.93	15.21	31.93	4.24
West Beck	42.99	18.96	42.99	5.87
Esk at Six Arch Bridge	98.88	33.04	98.88	6.41
Esk at Danby (A)	107.49	17.24	107.49	15.41
Esk at Danby (B)	107.49	17.24	107.49	8.50
Esk at Duck Bridge	114.73	13.33	114.73	14.05
Esk at Lealholm	143.57	19.90	143.57	12.79
Esk at Glaisdale	186.81	26.09	186.81	24.95
Esk at Egton Bridge	199.44	24.35	199.44	29.56
Esk at Grosmont	297.24	37.99	297.24	24.75

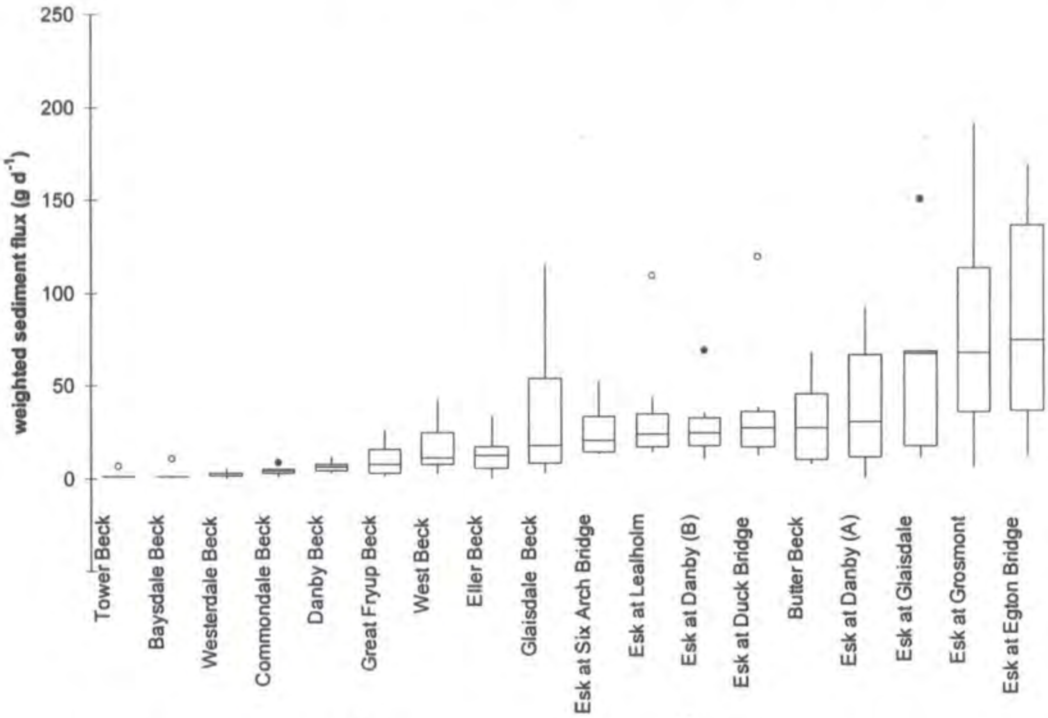


Figure 5.4: Box plots of weighted sediment fluxes (g d^{-1}) from mass flux samplers ordered by median sediment flux

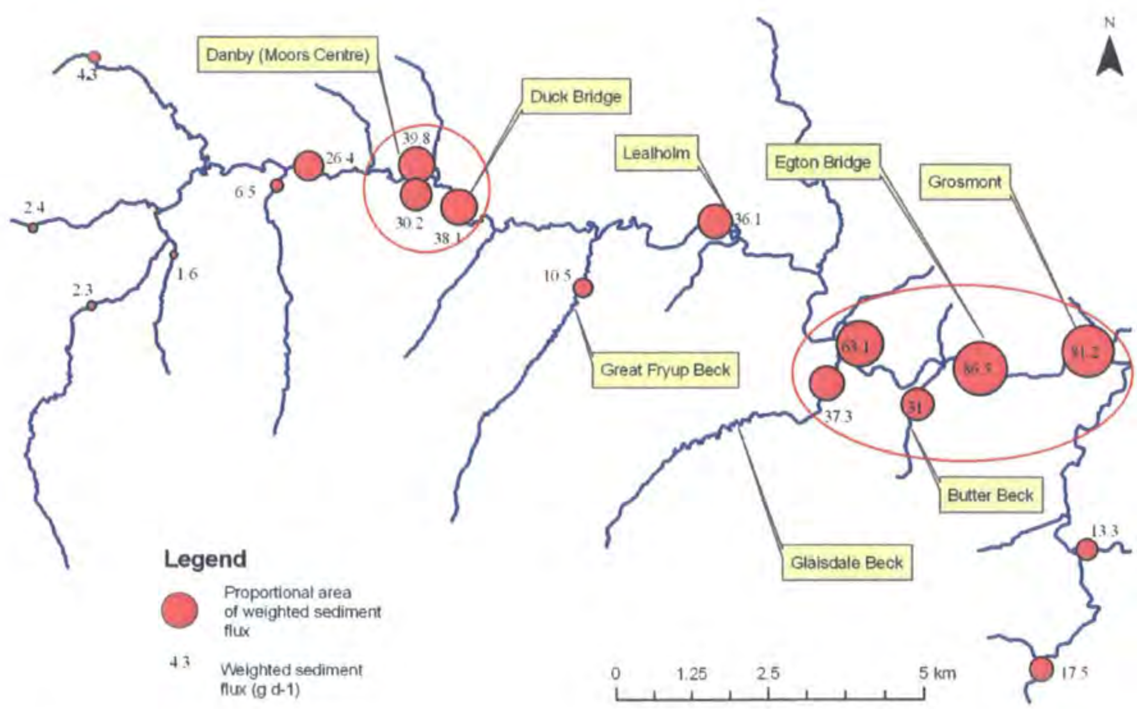


Figure 5.5: Mean weighted sediment flux (g d^{-1}) retained in the TIMS (transparent circles indicate fine sediment 'hotspots')

When the weighted sediment fluxes are compared to the contributing catchment area for each TIMS (Figure 5.6), a good relationship can be seen between increasing catchment area and increasing sediment load ($R^2 = 0.85$). This would be expected since these sediment fluxes are weighted by cross sectional area, which is correlated to catchment area.

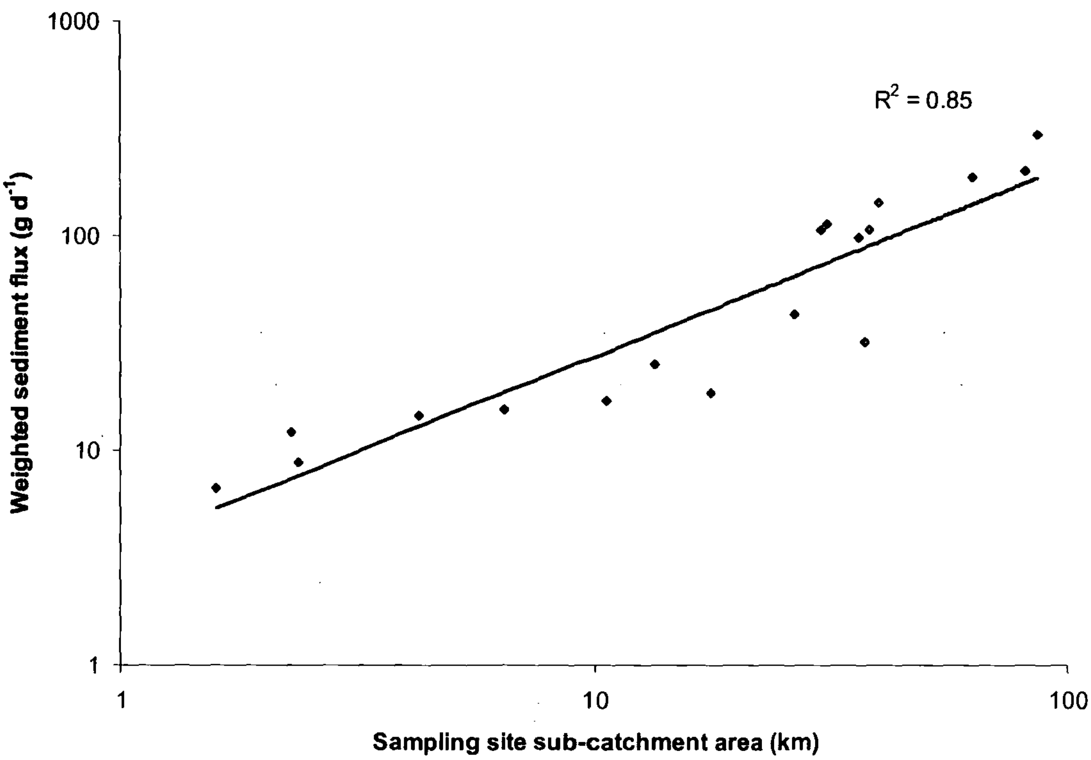


Figure 5.6: Comparison of mean weighted sediment flux (g d^{-1}) and sub-catchment areas of each TIMS sampling site ($R^2 = 0.85$)

5.2.3 Site specific sediment yields

It is well established that the sediment flux obtained at a particular sampling point from the TIMS sampler, is also influenced by the size of the catchment that drains to the sampler; thus, in addition to cross sectional area, the sampler sediment yield should also be weighted to account for catchment area. This was done by dividing the weighted sediment flux (g d^{-1}) by the site specific catchment area (km^2) (Table 5.1) for each given TIMS site, providing a site weighted specific sediment yield (g d^{-1} km^{-2}).

When displayed as proportional circles on the River Esk map (Figure 5.7), the importance of Butter Beck, Glaisdale Beck, Great Fryup Beck and Danby Beck in contributing fine sediment to the Esk network is clearly shown. In contrast, plotting site specific sediment yields decreases the significance of the TIMS sites on the main Esk. While site specific sediment yields are useful for highlighting the importance of the smaller tributaries in supplying fine sediment, the role of in-channel sediment sources for the main channel are greatly underestimated.

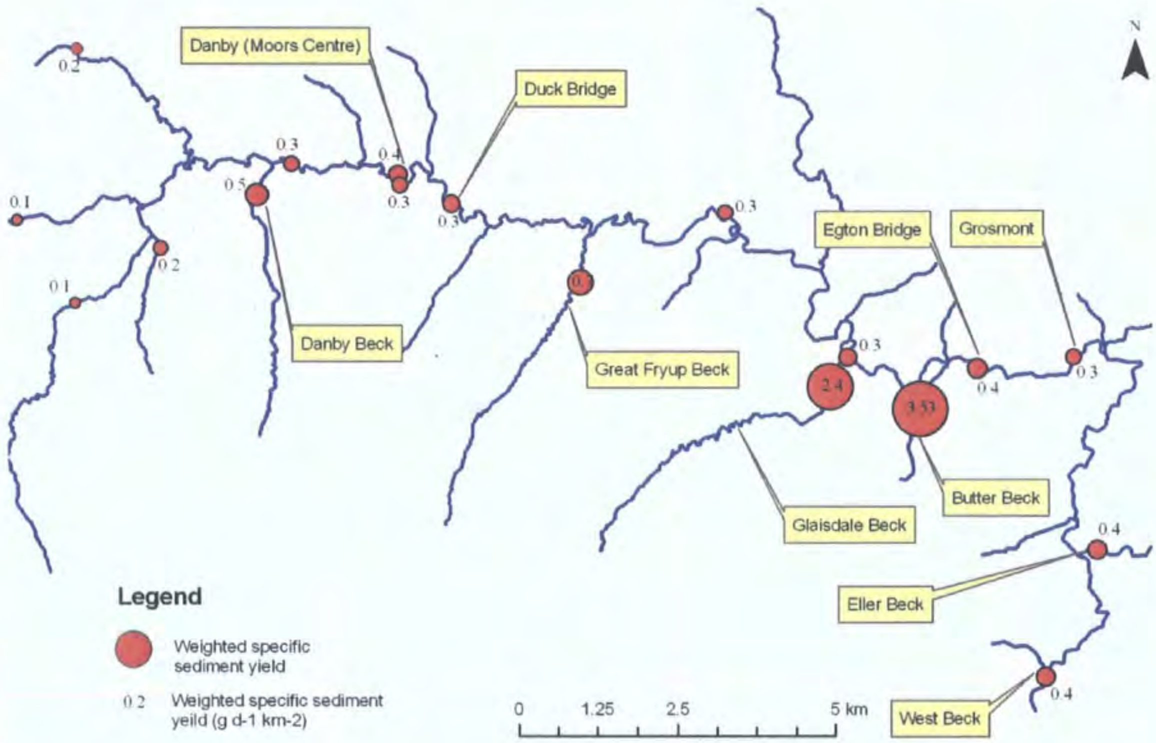


Figure 5.7: Mean weighted site specific sediment yields (g d^{-1} km^{-2}) retained in the TIMS.

When site specific sediment yields are compared to catchment area, a poor linear relationship can be observed ($R^2 = 0.09$) (Figure 5.8). However, Butter Beck and Glaisdale Beck are two anomalies in this relationship, as both have very large specific sediment yield to a relatively small catchment area. Subsequently this suggests that these catchments are characterised by high rates of erosion, little sediment storage and high hillslope to river connectivity, indicating a dominance of catchment sources. These suggestions are explored in greater detail in Chapter 6, which examines the results of the catchment mapping.

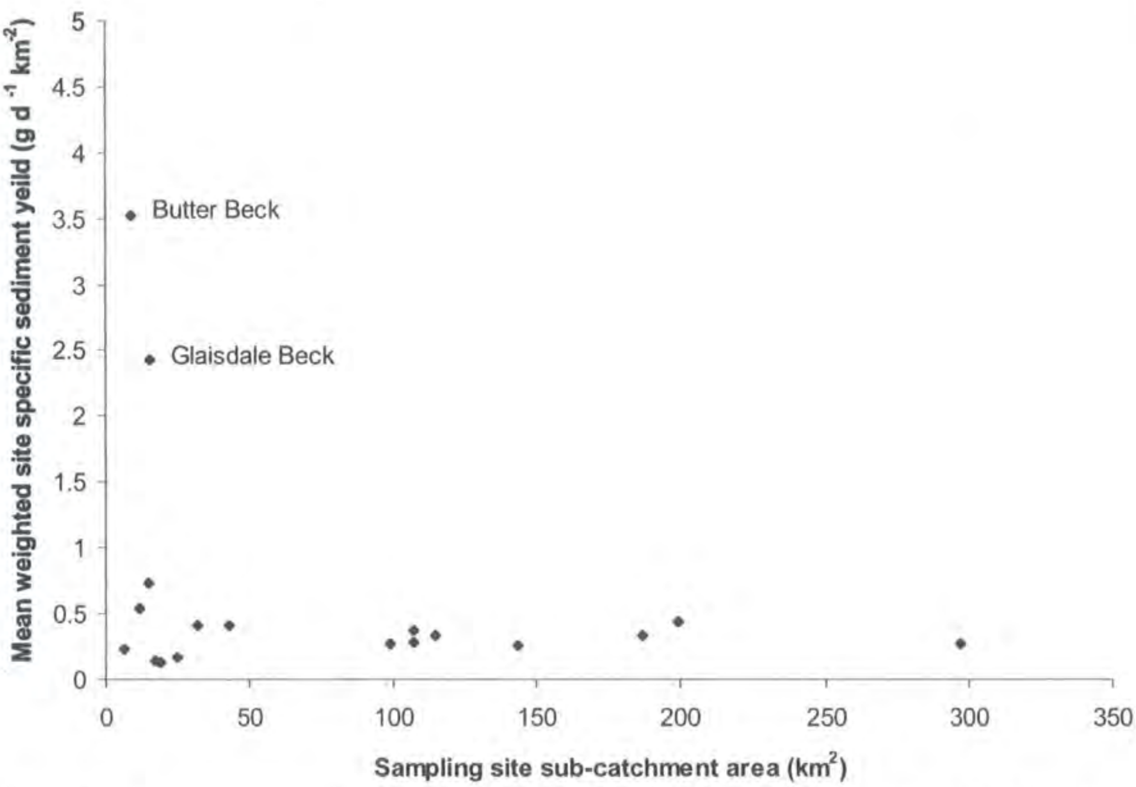


Figure 5.8: Comparison of mean weighted site specific sediment yields (g d^{-1} km^{-2}) and sub-catchment areas of each TIMS sampling site ($R^2 = 0.09$) (Butter Beck and Glaisdale Beck are highlighted as anomalies)

To summarise so far, these results highlight two 'hotspots' in fine sediment flux; the first being from Danby to Duck Bridge and the second being from Glaisdale to Gromont on the main Esk. Secondly, these results suggest that presenting a weighted sediment flux is the most effective way of displaying sediment transfer for the Esk catchment since the spatial variability of channel dimensions and site specific capacity is accounted for.

5.3 Storm 'gulp' samples

To provide a more detailed spatial pattern of fine sediment transfer, point 'gulp' samples were collected from the 17 TIMS sampling sites plus 20 additional sites during two periods of high flow (9/11/05; 20/05/06) (Figure 4.1). Although not directly comparable to the sediment flux retained in the TIMS, data from these suspended sediment concentrations do provide an indication of the response of different source and 'hotspot' location in suspended sediment during storms. The storm samples also provide preliminary information on the suspended sediment dynamics of some of the smaller tributaries not monitored up by the TIMS, such as Busco Beck, Little Fryup Beck, Cold Keld Beck and Plantation Beck (Figure 5.9).

When these suspended sediment concentrations are displayed as proportional circles on the Esk river network, large concentrations were observed on the section of main Esk between Glasidale Beck and Egton Bridge, especially during 20/05/06 flood (Figure 5.9B). In addition, high suspended sediment concentrations were also found in the four main tributaries (Butter Beck, Glaisdale Beck, Cold Keld Beck and Plantation Beck) draining into this section of the main Esk; thus implying during storms large amounts of fine sediment are mobilized and transported via these tributaries. The Murk Esk and Eller Beck, which enter the main Esk at Grosmont, as well as Little Fryup Beck, Great Fryup Beck and Busco Beck also appear to be contributing large amounts of suspended sediment to the main Esk during storms. In contrast, the area between Danby and Duck Bridge, identified as having high sediment fluxes (Section 5.2), have comparatively lower suspended sediment concentrations during higher flows. The tributaries supplying this section of the Esk, such as Danby Beck, Tower Beck, Baysdale Beck and Commondale Beck, also had low suspended sediment concentrations during storms.

However the validity of these point sample suspended sediment concentrations are limited due to the variability in cross sectional area between sampling sites. For example, in smaller tributaries with lower discharges and smaller channel capacities, proportionally a higher mass of suspended material will be collected in each point sample. Therefore, the concentrations collected in the smaller tributaries, such as Cold Keld Beck, plantation Beck and Butter Beck, maybe over emphasized relative to concentrations collected at large reaches such as Grosmont.

In summary, although the suspended sediment concentrations collected from storm 'gulp' samples are not directly comparable to the TIMS sample so must be treated with caution, large amounts of sediment were observed to be mobilised and transported in the between

Glaisdale and Grosmont (Figure 5.5) and its associated tributaries (e.g. Great Fryup Beck, Glaisdale Beck and Butter Beck).

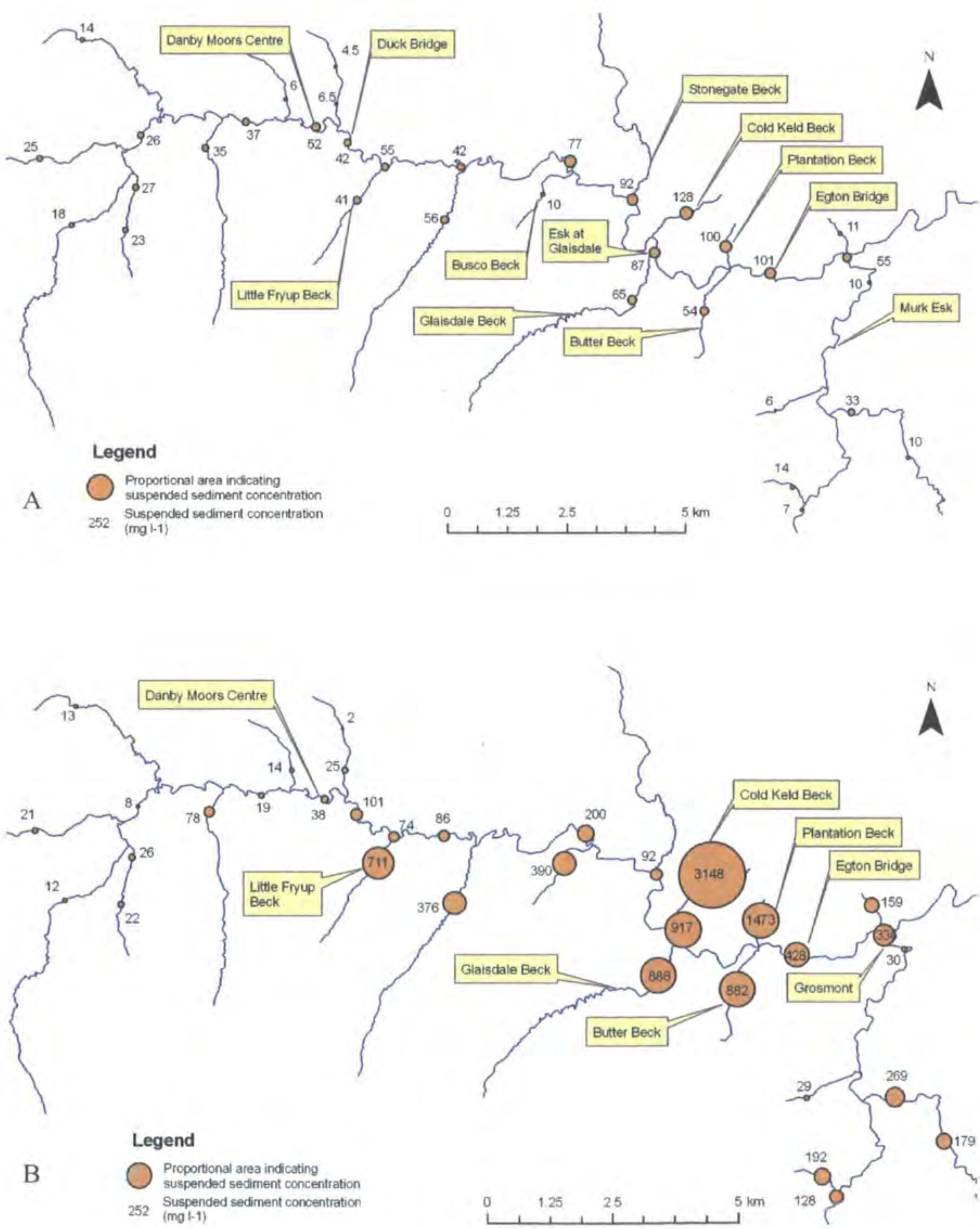


Figure 5.9: Mean suspended sediment concentrations (mg l^{-1}) collected from storm 'gulp' samples during high flows storm events: (A) 9/11/06; (B) 20/05/06

5.4 Temporal trends

Since 90% of material moved in a river basin occurs during high flow conditions (Walling, 1990) it is vital to understand the influence of high flow events on spatial patterns of fine sediment flux. Identifying temporal patterns in fine sediment transfer allows predictions to be made of how the catchment will respond during storms; which is crucial in creating effective management strategies targeted at lowering rates of sedimentation.

Temporal trends in suspended sediment dynamics were measured in the Esk catchment by examining the variability in sediment fluxes retained in the TIMS over the seven sampling periods the samplers were deployed (December 2005 – June 2006); (Table 5.2). This provided a winter to summer seasonal comparison of the spatial trends in fine sediment flux (Section 5.4.1). Weighted sediment fluxes retained from the TIMS were used to investigate temporal trends since these provide the best estimates of fine sediment transfer in the Esk catchment (Section 5.2.).

Table 5.2: Mean weighted sediment flux, peak stage and total rainfall (Danby) for each sampling period that the TIMS were deployed

Sampling period	Period of deployment	Days	Weighted sediment flux ($g\ d^{-1}$)	Standard Deviation	Peak stage (m)	Total rainfall (mm)
1	14/12/05-12/01/06	29	24.31	29.20	1.78	48.4
2	12/01/06-01/02/06	20	8.92	9.25	0.83	20
3	01/02/06-23/02/06	21	21.50	22.62	1.24	33.6
4	23/02/06 – 21/03/06	27	26.61	37.68	2.73	87.2
5	21/03/06 – 20/04/06	30	37.68	35.06	2.42	91.8
6	20/04/06 – 16/05/06	26	8.21	6.74	0.71	41.8
7	16/05/06 – 05/06/06	20	64.22	62.20	4.70	79.6

The effect of flow conditions and storm frequency were also examined by comparing the spatial distribution of sediment fluxes collected for each sampling period with stage and rainfall records collected from the gauging station at Danby. Although using data collected from the one gauging stations limits the extent to which spatial comparisons within the catchment can be made, this is minimised given the small nature of the catchment area. Since it is the high flow events that are important in terms of fine sediment transfer, mean peak stage for each sampling period is used (Table 5.2). This will provide an indication of the influence of flow conditions within channel and their significance in contributing fine sediment to the Esk during high flow events (Section 5.4.2). Additionally, total rainfall (mm) is used, again in relation to the sediment fluxes retained in the TIMS to examine the catchment response during storms in terms of sediment inputs and dominant sediment sources (Section 5.4.3).

5.4.1 Seasonal trend in weighted sediment flux

Figure 5.10 shows that suspended sediment fluxes collected in the TIMS for each sampling period are highly variable, suggesting temporal, as well as spatial, controls are governing the fine sediment transfer in the Esk catchment. In particular sampling periods five and seven were found to yield the highest suspended sediment fluxes; whereas sampling periods two and six had the lowest.

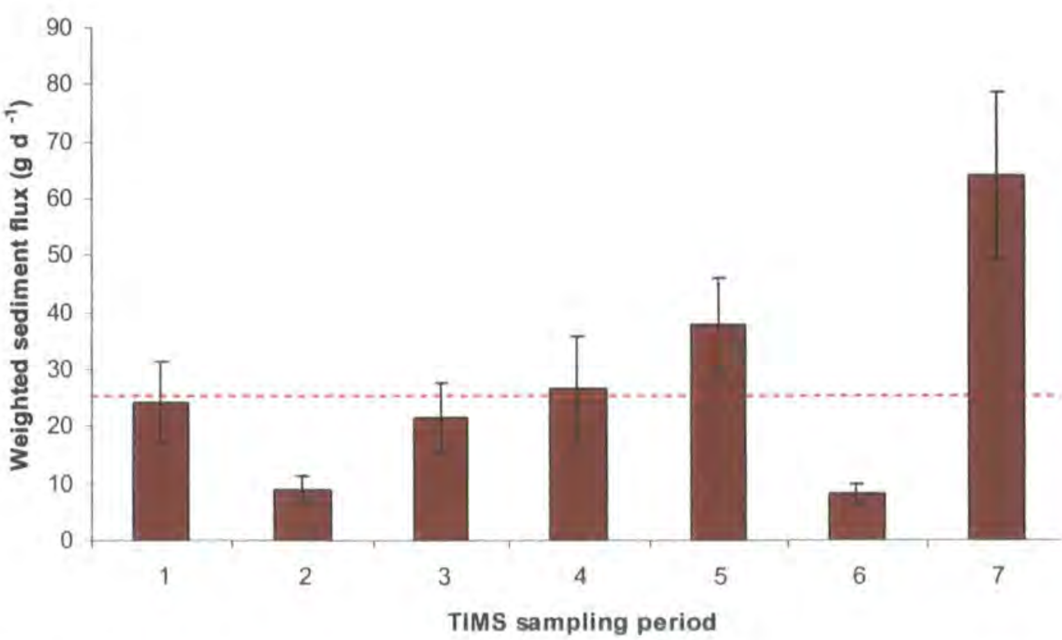


Figure 5.10: Mean weighted sediment fluxes (g d^{-1}) retained from the TIMS for each sampling period (red line indicates mean weighted sediment flux over all sampling periods)

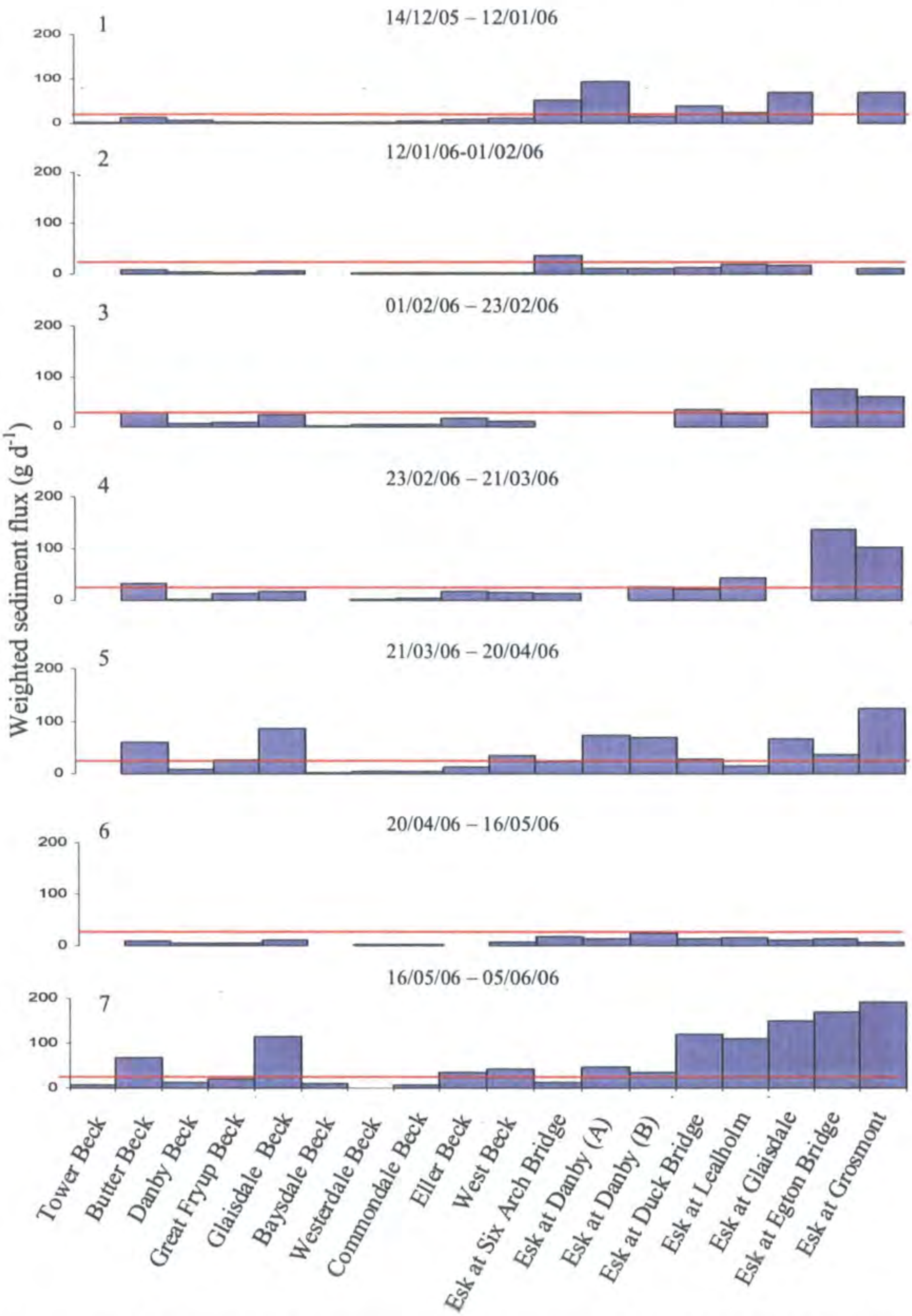


Figure 5.11: Temporal trends in mean weighted sediment flux (g d^{-1}) retained from the TIMS for each sampling period (1 – 7)

Looking at these temporal trends in suspended sediment flux in more detail for each TIMS site (Figure 5.11) provides further confirmation that suspended sediment fluxes are variable between sampling periods, but that certain sites, such as Grosmont, Egton Bridge and Glaisdale on the main Esk, are more temporally variable in comparison to sites such as, Tower Beck, Westerdale Beck and Commondale Beck. That is to say, the sites observed to have the highest suspended sediment flux have the greatest variability between sampling periods. This could indicate that the dominant sediment sources contributing to the load at these sites are more responsive in high flow conditions (e.g. in-channel fine sediment storage).

5.4.2 Weighted sediment flux and peak stage

To establish the affect of high flow conditions on spatial dynamics in sediment transfer, mean weighted sediment fluxes from all TIMS samplers over all the sampling periods were compared with peak stage levels (m) (Figure 5.12).

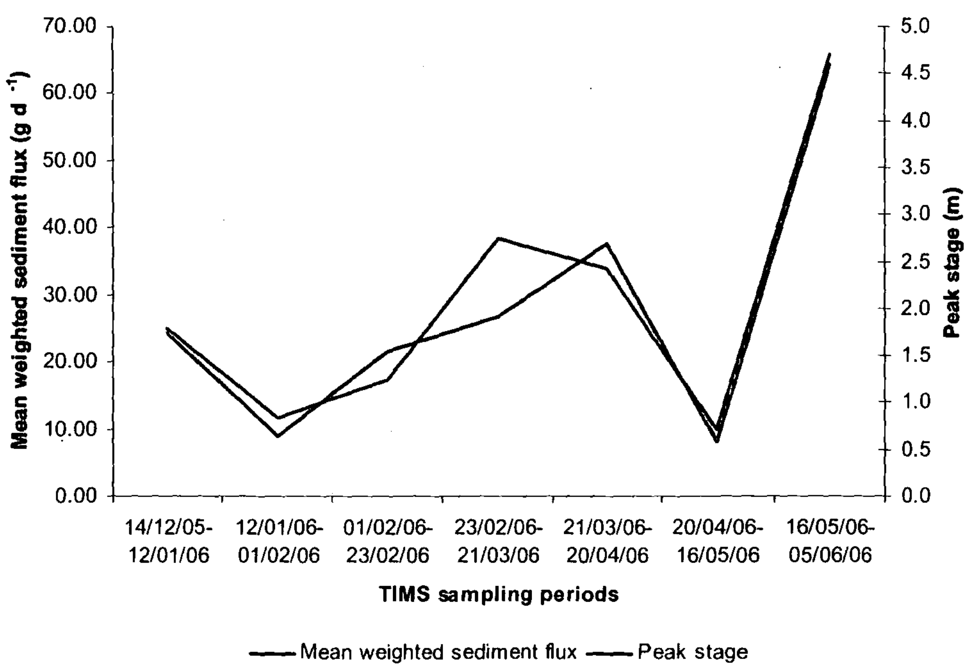


Figure 5.12: Peak stage records (m) (blue) and mean weighted suspended sediment flux (g d^{-1}) (brown) obtained from the TIMS for the 7 sampling periods (December 2005 – June 2006).

A very strong relationship can be observed ($R^2 = 0.93$) (Figure 5.13). This would be expected since with increased flow there is increased energy available for entrainment and transport and the channels have a greater capacity for transporting larger sediment yields further distances. Additionally, the wetted perimeter of the channel is increased so more sediment sources and stores can be activated and mobilised. These results therefore suggest that large amounts of sediment are being transported and deposited through the Esk catchment in response to high flow conditions and low to moderate flows contribute less to the fine sediment flux.

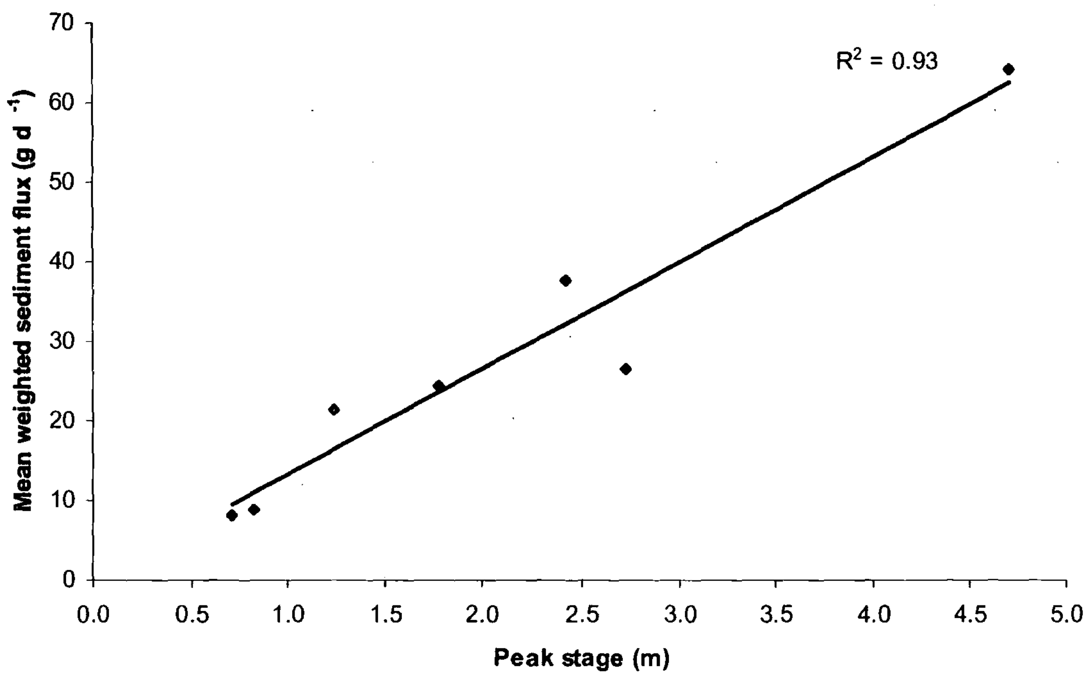


Figure 5.13: Comparison of peak stage records (m) and mean weighted sediment flux (g d^{-1})

However, this fine sediment flux-peak stage flow relationship is not so clear cut. For example in sampling period 4 (23/02/06 – 21/03/06), peak in stage level is relatively high in comparison to the low sediment fluxes (Figure 5.12). This would suggest that the temporal trends on the suspended sediment fluxes are not solely influenced by flow patterns and that there are other governing factors controlling the temporal patterns observed, such as spatial patterns in rainfall (5.5.3), episodic occurrences of bank failures, the TIMS being partially blocked by floating debris and antecedent conditions of the hillslopes draining into the Esk.

Using the mean weighted sediment fluxes collected from the TIMS provides a broad overview of controls of flow on spatial sediment dynamics but greatly conceals the spatial variability between different TIMS sampling sites. To demonstrate this variability, temporal trends in sediment loads observed at Danby (gauging station) and Butter Beck were compared with peak stage levels (Figure 5.14). These sites are both characteristic of high sediment fluxes, yet have very different responses to high flow conditions.

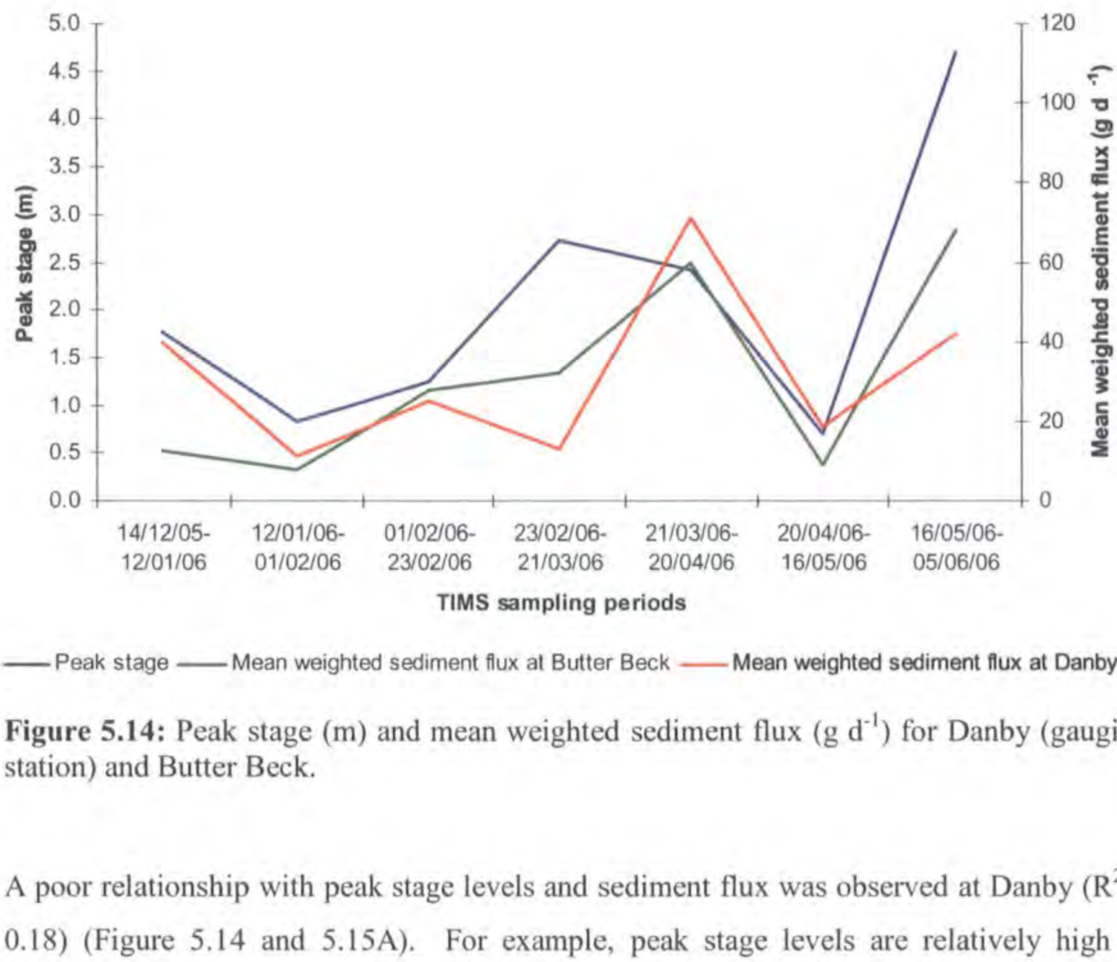


Figure 5.14: Peak stage (m) and mean weighted sediment flux (g d^{-1}) for Danby (gauging station) and Butter Beck.

A poor relationship with peak stage levels and sediment flux was observed at Danby (R^2 = 0.18) (Figure 5.14 and 5.15A). For example, peak stage levels are relatively high in sampling period four (23/02/06 – 21/03/06), yet sediment fluxes are comparatively lower. Since the stage record was collected next to the TIMS sampler at Danby, non-compatibility with the stage data cannot be attributed to this variability found. However this difference could indicate the dominance of the episodic sediment inputs from bank collapses. Hence at this location it is not so much flow variables that govern the amount of fine sediment transported and deposited, but the nature of the random occurrences of large bank failures.

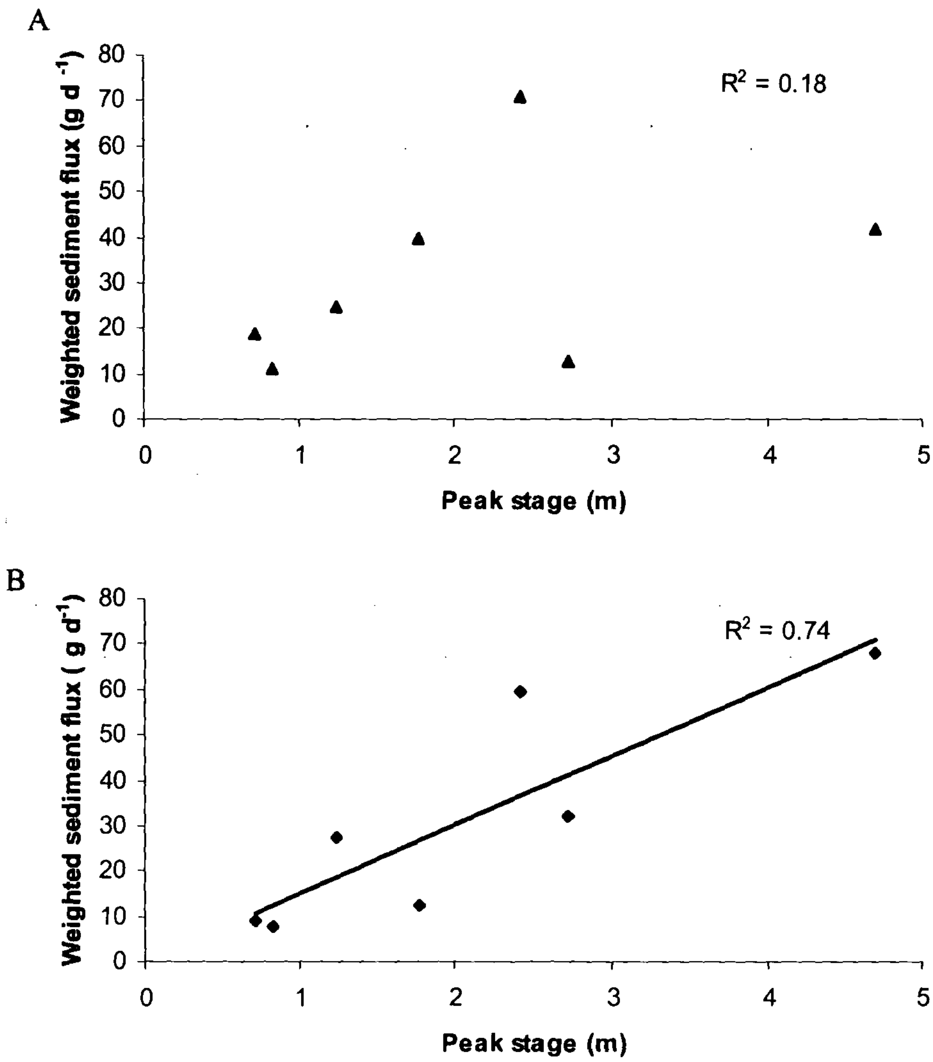


Figure 5.15: Comparison of peak stage records (m) and weighted sediment flux (g d^{-1}) at: (A) Danby (R^2 =0.11); and (B) Butter Beck (R^2 =0.74).

In contrast however, the temporal trends in suspended sediment loads at Butter Beck responded relatively closely with changes in peak stage (R^2 = 0.74) (Figure 5.14 and 5.15B). This suggests that the flow condition does have a significant influence over the high sediment fluxes collected at this tributary. One hypothesis explaining this could be due to a high occurrence of sediment retention mechanisms, such as debris log jams created from fallen trees, present in the tributary. Sediment would therefore be deposited and stored behind these obstructions during low flows, which will then be flushed out and deposited into the main Esk channel during high flows. However field observations on the characteristics of the channel are needed to further validate this hypothesis (Chapter 6).

5.4.3 Weighted sediment flux and rainfall

Due to its catchment wide influence, particularly from the hillslope to the channel, it is also necessary to consider the temporal response of fine sediment transfers to rainfall patterns. Mean weighted suspended sediment flux retained from all deployed TIMS samplers was compared with total rainfall (measured at Danby) for each TIMS sampling period (Figure 5.16). This shows broad similarities between larger total rainfalls and increased suspended sediment transfers. However the relationship between these two variables was not as strong in comparison to peak stage ($R^2 = 0.49$).

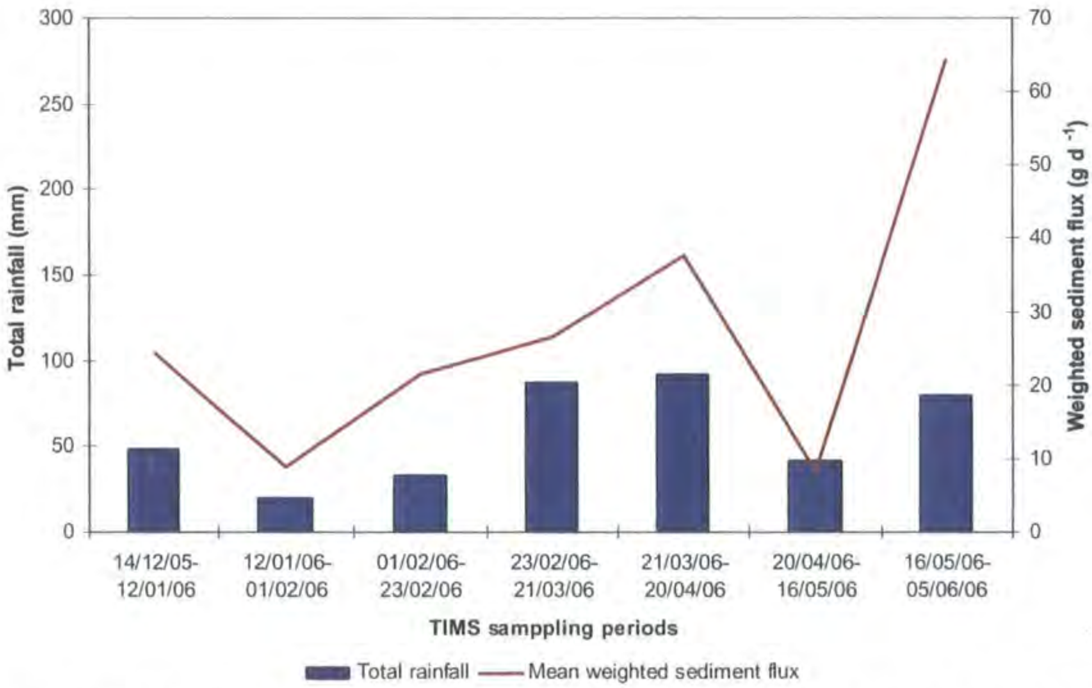


Figure 5.16: Mean sediment flux (g d^{-1}) retained from the TIMS samples and total rainfall (mm) (Danby)

However once again, the spatial variability of sediment transfers has been masked by using the mean sediment fluxes obtained from all sampling sites and owing to the spatial control of rainfall, may explain the poor relationship observed. To examine this relationship in more detail, sediment loads obtained at Danby and Butter Beck were compared to the total rainfall in each sampling period (Figure 5.17). Again a weak relationship between the total rainfall and weighted sediment fluxes obtained from Danby was observed ($R^2 = 0.20$). This further suggests that the sediment loads accumulated here are due to episodic of local bank inputs rather than from wider catchment sources. It is therefore probable that it is the antecedent condition of the banks that have larger controls of sediment inputs here. These are controlled by flow, rainfall events and soil moisture status, but are harder to measure and account for. In comparison, the sediment flux at Butter Beck have a stronger relationship with total rainfall ($R^2 = 0.63$) adding further confirmation to suggestions made in Section 5.2 and Section 5.4.2 that the dominant contributing sources here are from wider catchment sources rather than local bank sources.

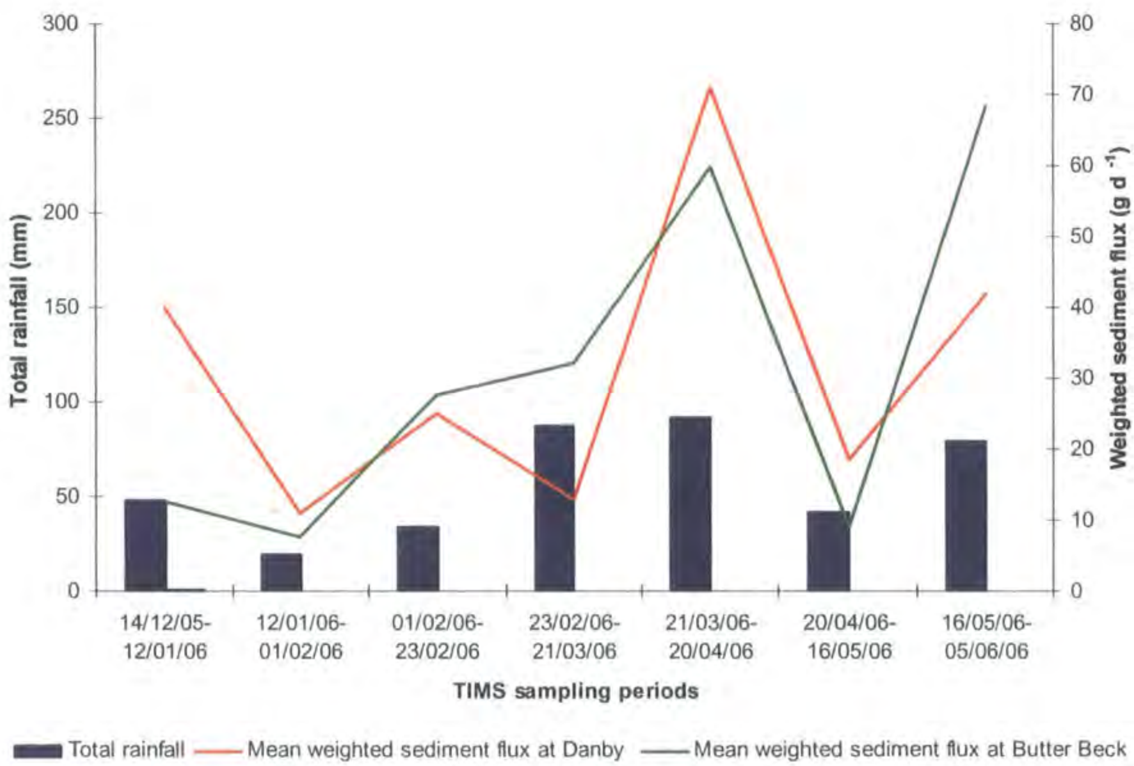


Figure 5.17: Weighted sediment flux (g d^{-1}) at Danby and Butter Beck retained from the TIMS samplers and total rainfall (mm)

However, these conclusions should be treated with caution as it is arguably rainfall intensity that is a more significant control in terms of fine sediment mobilisation and movement within the catchment. In addition, the total rainfall data were collected from one rain gauge at Danby and given the highly variable nature of rainfall, limits the extent to which this data set can be used to analyse catchment scale spatial patterns in fine sediment flux.

5.4.4 Temporal trends summary

In summary, while it is clear temporal controls, in addition to spatial controls, are governing the fine sediment transfer in the River Esk catchment, temporal relationships in sediment transport are complex. A strong relationship between spatially averaged fine sediment flux and peak stage was observed which indicates that large amounts of fine sediment are mobilized and transported through the Esk catchment during high flow conditions. However, considerable variability at individual TIMS sampling sites was also observed. For instance at some locations, such as Duck Bridge, flow patterns were not found to be the dominant control on the temporal trends in fine sediment flux, suggesting episodic occurrences of bank collapses may contribute to the high sediment loads identified in this section.

A weaker relationship between fine sediment flux and total rainfall (R^2 = 0.49) was also highlighted suggesting that other factors, such as runoff variability, antecedent hillslope condition, temperature, seasonal patterns in vegetation cover and land use management practices, are also influencing the observed temporal trends in suspended sediment flux obtained from the TIMS. Additionally, the random occurrence of the TIMS being blocked by floating debris may also influence the temporal trends in fine sediment found. Lastly, due to the relatively short six month period that the TIMS were deployed (from December 2005 – June 2006) it is hard to assess the representativeness of these patterns of longer term temporal trends. Nevertheless, based on the observed temporal trends it is clear significant amounts of fine sediment are being mobilized and transported through the Esk catchment during high flow conditions and high sediment fluxes at Danby and Glaisdale to Grosmont in the River Esk can be identified as problematic fine sediment 'hotspots'.

Chapter Six: SIGNIFICANCE OF CHANNEL AND CATCHMENT CHARACTERISTICS

6.1 Overview

Catchment characteristics are important controls on the nature of suspended sediment supply and transfer; hence are essential considerations when examining spatial patterns of fine sediment flux. Channel and catchment attributes (such as bank height, vegetation cover, erosion extent and land use of the riparian zone) were mapped and plotted into ArcGIS to create a GIS database of catchment characteristics. These can then be compared to the observed spatial and temporal patterns in fine sediment flux (Section 5.2) to elucidate trends and to identify dominant source areas (Chapter 7).

This chapter is split in to two parts: Firstly local scale channel bank characteristics, such as bank height, bank material, bank vegetation cover and type are examined (Section 6.2.1 - 6.2.3) in relation to erosion type and extent (Section 6.3) and channel bank management (Section 6.4). This is done to establish the role of channel banks in supplying fine sediment to the Esk catchment. Secondly, land use, slope and geology are considered in terms of spatial trends of channel attributes (Section 6.5.1 - Section 6.5.4) and fine sediment flux (Section 5.2), to examine larger scale catchment controls and dominant sediment sources.

6.2 Channel bank characteristics

6.2.1 Bank height

Bank height is an important attribute to consider in terms of channel bank stability and erosion. It is expected that the higher the channel bank, the greater the instability and hence the higher the rate of sediment supply. Mean bank height was examined by averaging the height of both banks in each geomorphologically defined reach and are displayed on the River Esk map. The darker shade of blue indicates higher bank heights (Figure 6.1).

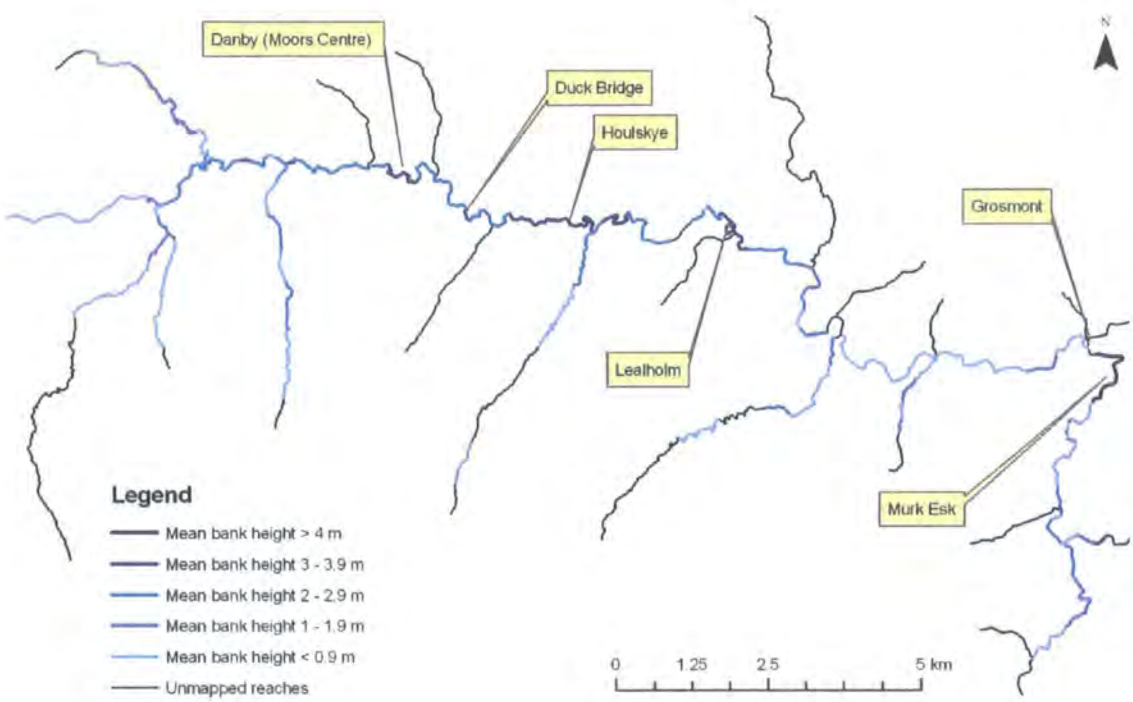


Figure 6.1: River line map illustrating mean bank height

The channel heights were greatest on the middle section of the main Esk, especially at Danby (Moors Centre), Duck Bridge, Houlskye and Lealhom and at the bottom of the Murk Esk (average heights: 4 m; 3.5 m; 4 m; 4 m; 5.5 m respectively). This is suggestive that the banks at these locations are of increased instability and are being incised; hence could be important sources of fine sediment inputs. In comparison, the heights of the channels were much lower in most of the tributaries and the section of the main Esk below Lealholm to Grosmont, which implies that the channel banks were of increased stability in these sections; so less important in terms of sediment delivery. Averaging the heights of the two banks could potentially create sources of error where the bank heights in a reach are substantially different; however in general both bank heights were of similar heights so the errors here are minimal.

6.2.2 Bank material

The material that makes up the channel bed and banks determines the geotechnical stability of the banks and resistance to erosion. This is important in terms of fine sediment supply because the size, shape and density of the bank sediment once in suspension governs the ease of erosion, distance transported and location deposited. Mapping the spatial distribution of bank material properties also helps when inferring the importance of in-channel sediment sources to local sediment yields. For each mapped reach the dominant material for each bank was classified into one of the following categories; sand, fines, gravel, artificial or bedrock (in approximate order of resistance to erosion). Opposite banks in a reach were usually made up of the same material, however where the dominant material for both banks differed, a mix of material is displayed (Figure 6.2).

Most of the bank material from the top of the main Esk down to Houlsyke appears to be predominantly sandy. Sandy soils are more vulnerable to erosion in comparison to bedrock and boulder material, as the particles are less cohesively bound together so fall apart more easily. These sandy materials, in combination with the presence of high channel banks, suggest this is a potential area of significant inputs of sediment. Towards the bottom of Commondale Beck and Great Fryup Beck the bank material is also predominantly sandy but the presence of the lower bank heights (Figure 6.1) suggests that these areas represent less significant sediment inputs.

At Westerdale Beck, Tower Beck, Danby Beck and parts of the main Esk, near the mouth of Stonegate Beck, the bank material is predominantly fine and could again represent potential inputs of fine sediment. Below Glaisdale, and for the tributaries of Butter Beck and Glaisdale Beck, the presence of boulders and bedrock banks dominate. Given the lower bank heights observed here (Figure 6.1) this suggests these banks do not represent such significant sources of fine sediment. Observations of the dominant bank material can be obstructed by vegetation growth. However, since the majority of the field observations were carried out in winter when the vegetation and trees covering the bank were less extensive, this error was minimised.

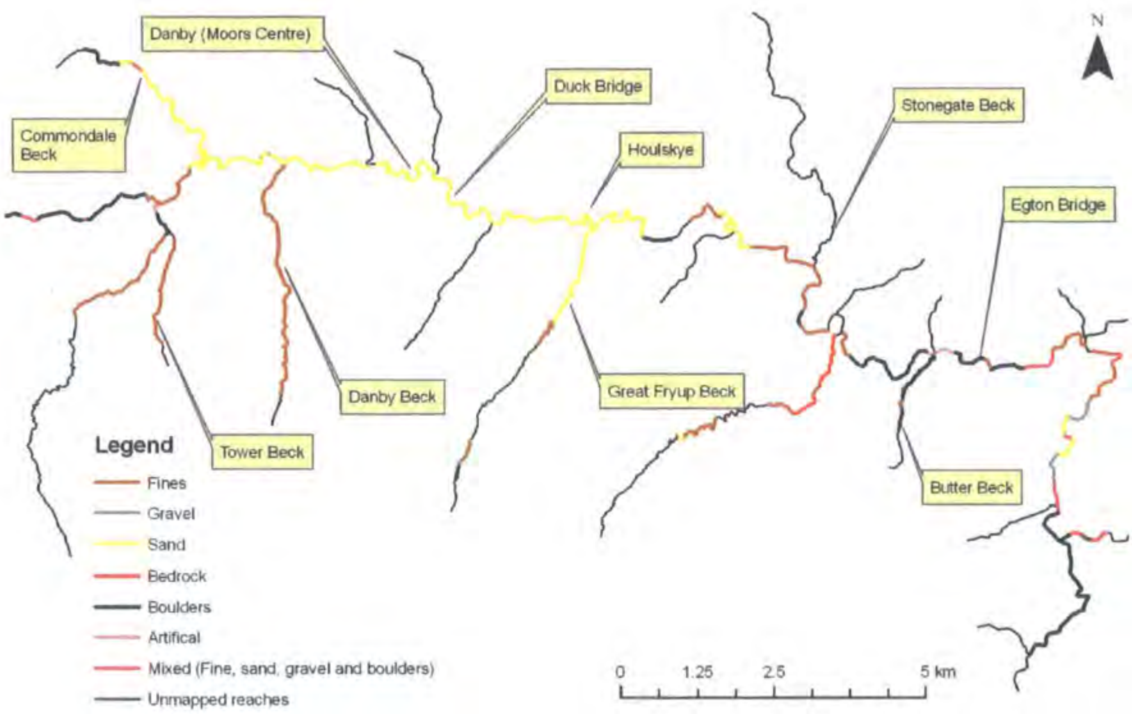


Figure 6.2: River line map illustrating dominant bank material

6.2.3 Vegetation cover

Bank vegetation cover also influences the amount of sediment eroded from the banks because plant roots bind and consolidate the bank material. Vegetation cover was mapped for the Esk catchment by estimating the percentage cover for each bank in the surveyed reaches. A mean vegetation cover was then created by averaging the two banks (Figure 6.3).

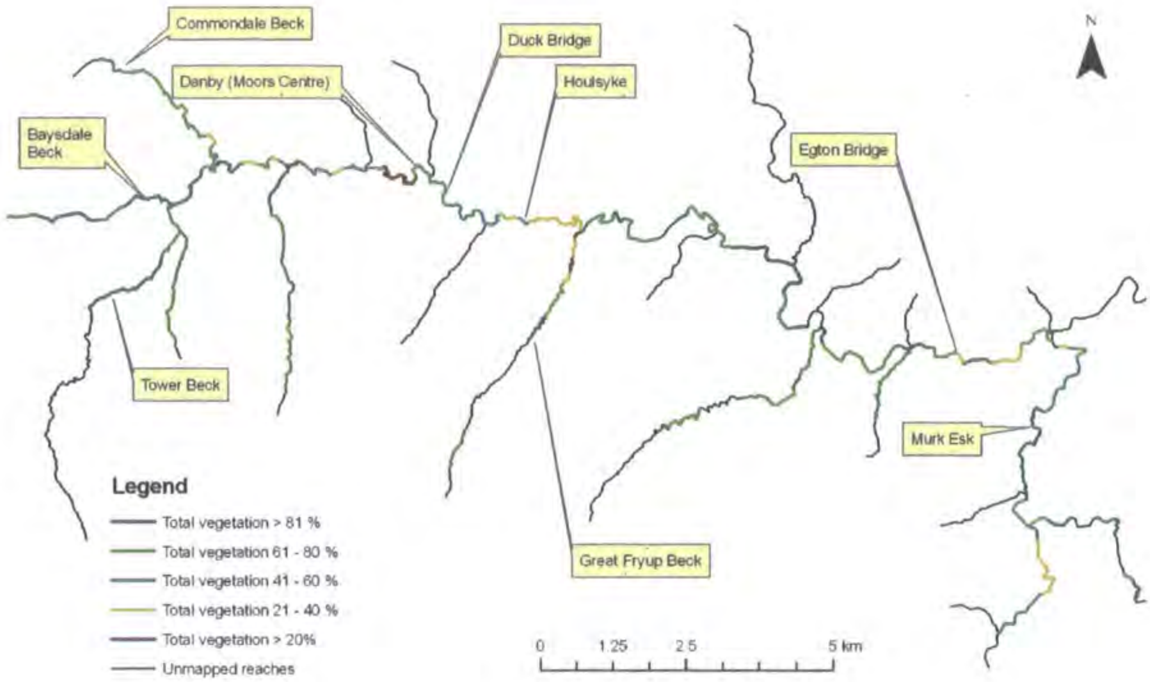


Figure 6.3: River line map illustrating mean total vegetation cover (%)

Total vegetation cover was found to be lowest on the main Esk at Danby (Moors Centre) and Houlskye (average 12 % and 35 % respectively), suggesting increased instability and higher rates of erosion at these locations. The vegetation cover was also sparse at the bottom of Great Fryup (average 35%). In contrast, most of the tributaries draining into the Upper Esk near Danby are relatively well vegetated (e.g. Baysdale: 85 %; Tower Beck: 80 %; and Commondale: 60 %), which would be expected given the low suspended sediment fluxes observed (Section 5.2). With respect to the lower section of the main Esk near Egton Bridge, vegetation cover is higher (average 75 %); yet sediment supply was also high, which implies that in the lower Esk channel banks below Lealholm, in comparison to Danby, are a less significant fine sediment supply.

The type of vegetation present also governs the extent to which the channel bank is incised and eroded by the flow. This was broadly mapped by estimating the proportion of the vegetation cover for each surveyed reach as woody and non-woody, which was then averaged for both banks. The following vegetation types were then classified using the proportions of vegetation cover that were woody and non-woody:

- Trees: where over 30 % of the vegetation cover was woody;
- Grass, shrubs and weeds: where over 50 % of the vegetation cover non-woody;
- Bare: where both woody and non-woody vegetation cover were both under 15 %.

The reaches that did not fall into these categories were classified as mixed (Figure 6.4).

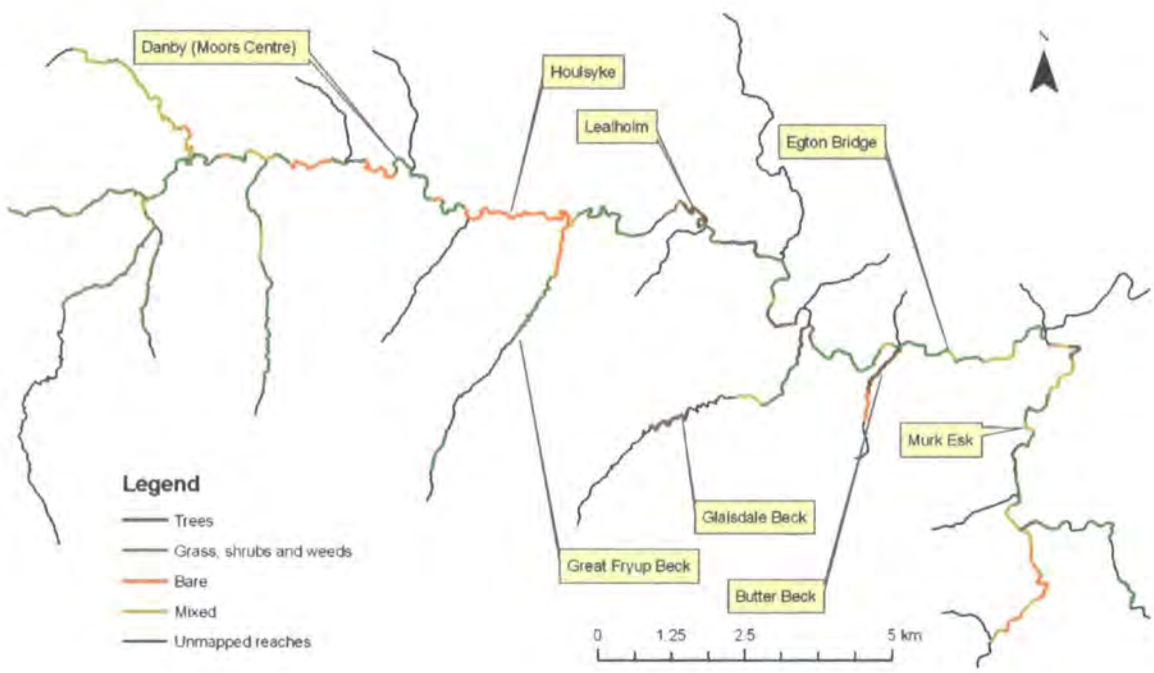


Figure 6.4: Vegetation type in the Esk catchment

Much of the vegetation type along the banks of the tributaries in the Upper Esk is predominantly grassy. Figure 6.4 further highlights the upper sections of the main Esk and the lower section of Great Fryup Beck as having extremely low vegetation covers. In contrast, sections of Glaisdale Beck, Butter Beck and the Murk Esk have high tree coverage, yet were also identified as having high sediment flux (Section 5.2). It is generally accepted that the presence of trees stabilise banks by binding the soil their roots; however these areas in the River Esk catchment do not conform to this. This could suggest that the channel banks here are not the dominant source of sediment, but rather more distant catchment sources; or that it is the trees themselves that are the dominant form of sediment inputs where they have fallen into the channel depositing large amounts of bank material with them (Figure 6.5). These trees can create debris jams causing sediment to build up behind them, which will then be released in large volumes during periods of higher flow.

Figure 6.5: Fallen tree in the channel creating a debris log jam in Glaisdale Beck

However, observations of total vegetation cover and type are strongly controlled by the season in which the field mapping was carried out. Here most of the channel mapping was carried out during winter when the extent of shrubs and trees lining the banks were lowest. To minimise this bias nearly all of the fieldwork was carried out in the same week providing consistent trends in vegetation cover between reaches.

6.3 Channel erosion

6.3.1 Erosion extent

The extent and type of erosion was also mapped for each river reach in the Esk catchment. This provides clues about the location of dominant sediment inputs and can also be used in combination with the channel characteristics (identified in Section 6.2) to ascertain the dominant controls on spatial patterns of fine suspended flux at the channel scale. The extent of erosion was mapped using a qualitative classification scale of 0 - 4 (Table 6.1). Since the erosion extent observed for both banks in each reach was nearly identical, the results of only the left bank are displayed on the River Esk map (Figure 6.6).

Table 6.1: Description of erosion extent classifications used

Erosion extent classification	Description
4	Very extensive erosion
3	Substantial areas of erosion
2	Small sections of eroding banks in a dominantly stable reach
1	Very little erosion evident
0	No erosion

The tributaries draining the Upper Esk appear to have relatively extensive erosion (e.g. Commondale Beck and Westerdale Beck have average erosion extents of 3). This could relate to the dominance of the poorly cohesive sand and fine bank material (Figure 6.2). However, given the extent of erosion found in these tributaries the observed sediment fluxes were low (Section 5.2). This may indicate that while these reaches have contemporary low yields, it is possible that the erosion features observed pre-date these and that the sediment inputs have already been deposited into the river system.

The highest extent of erosion was identified on the main Esk near Danby which correlates well with the high sediments fluxes obtained from the TIMS (Figure 5.5). This is not surprising given the nature of the high, sandy banks with low vegetation cover identified in

Section 6.2 (Figure 6.7). This suggests the high sediment yields at Danby are a result of local bank material being deposition on the bed as a consequence of the unstable channel banks. Adding further weight to this hypothesis, large amounts of failed material was observed at the foot of these high, unstable sandy banks at Danby during field mapping (Figure 6.8).

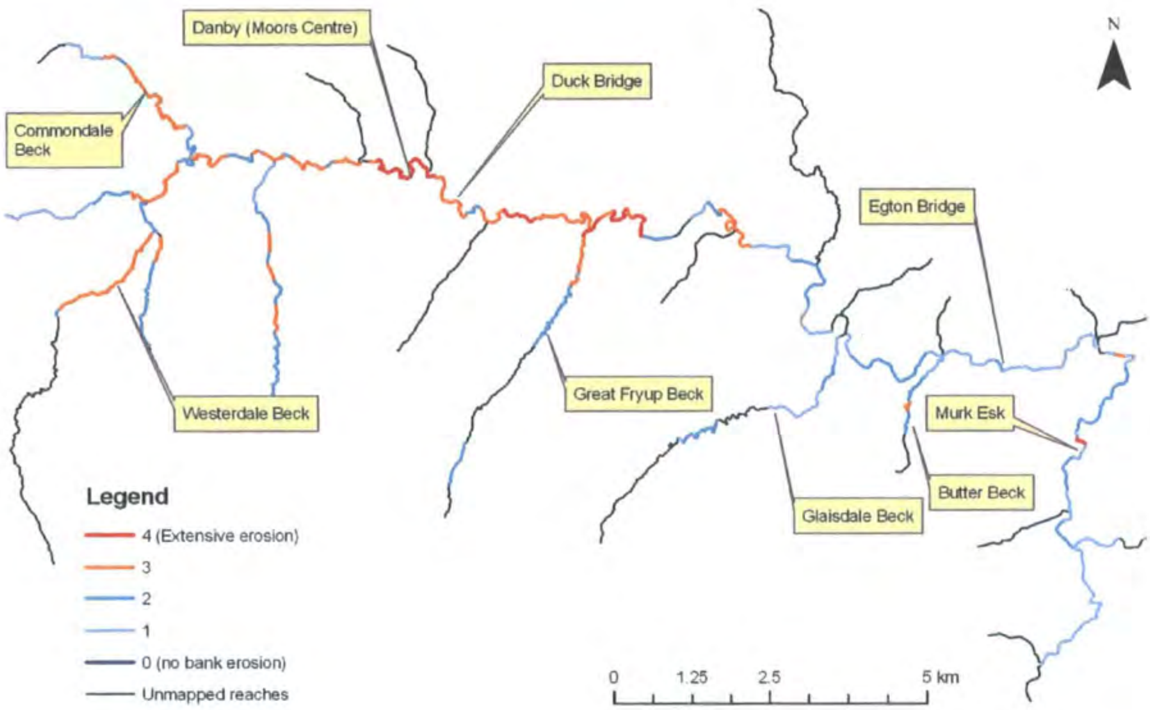


Figure 6.6: River line map illustrating left bank extent of erosion

Figure 6.7: Steep, unvegetated sandy bank near Danby (Moors Centre) main Esk

Figure 6.8: Extensive sand deposits at foot of steep, unvegetated sand banks near Danby (Moors Centre) main Esk

In comparison, the extent of erosion mapped on the main Esk between Glaisdale to Grosmont is lower (Figure 6.6). Again this would be expected given the lower, well vegetated, predominantly boulder and bedrock channel banks found here, again as identified in Section 6.2 (Figure 6.9). This suggests the channel banks of the main Esk here are not as significant in terms of fine sediment supply. However, the sediment flux retained in the TIMS for this section of the main Esk were high (Section 5.2). One hypothesis explaining this trend is that the high sediment loads are the result of more distance catchment sources being transported, supplied and deposited in this section of the Esk.

Figure 6.9: Low, well vegetated, boulder banks below Lealholm (main Esk)

Likewise, the tributaries Glasidale Beck, Butter Beck, Eller Beck and the Murk Esk also exhibit less extensive erosion but displayed higher sediment flux (Section 5.2). This would again suggest that the channel banks here are also not the dominant sources contributing to high fine sediment yields to the Esk; which implies a greater contribution of catchment sources. However, observations drawn from the mapped erosion extent are limited by the subjective nature of them, which are dependant upon the fieldworker's individual perceptions of erosion extent, weather and field conditions.

6.3.2 Erosion vulnerability

To add further confirmation to the surveyed areas of erosion extent, using the geomorphological attributes in the database, a map was created by combining bank height, vegetation cover and bank materials. High banks, low vegetation cover and dominance of sand bank material are used to indicate where the vulnerability to erosion was the highest. Reaches with a vegetation cover less than 50 %, predominantly sand banks and bank height of over 4 m for each bank were identified and displayed as red sections on a river line map (Figure 6.10).

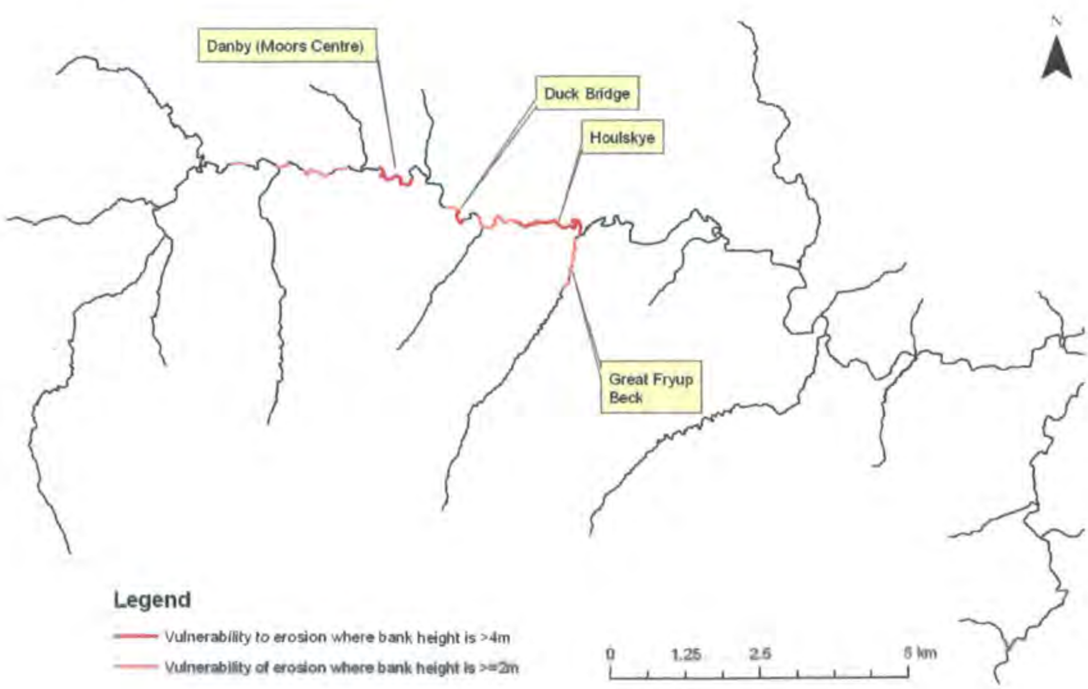


Figure 6.10: Indication of areas in the Esk catchment most vulnerable to erosion

This highlighted the reaches at Danby (Moors Centre), Duck Bridge and Houlsyke on the main Esk, which were also identified as having the most extensive erosion (Figure 6.6). Reaches where sand banks dominated and the vegetation cover was under 50 %, but the bank heights were 2 m and over additionally highlighted sections of the main Esk above Lealholm and lower sections of Great Fryup Beck (Figure 6.10); and further agrees mapped erosion extent (Figure 6.6).

6.3.3 Type of erosion

In order to understand the spatial variability in the extent of erosion it is necessary to identify the dominant type of erosion processes occurring within each surveyed reach. This was done by classifying the dominant erosion processes into one of the following categories; geotechnical (internal collapse such as slumping (Figure 6.13)); fluvial (material entrained by the river); tree scour (flow deflected round trees) and sub-aerial (rain splash or freeze thaw). Opposite banks in each surveyed reach generally had the same dominant type of erosion, but where two different erosion types were mapped for the two opposite banks, the erosion process was displayed as mixed (Figure 6.11).

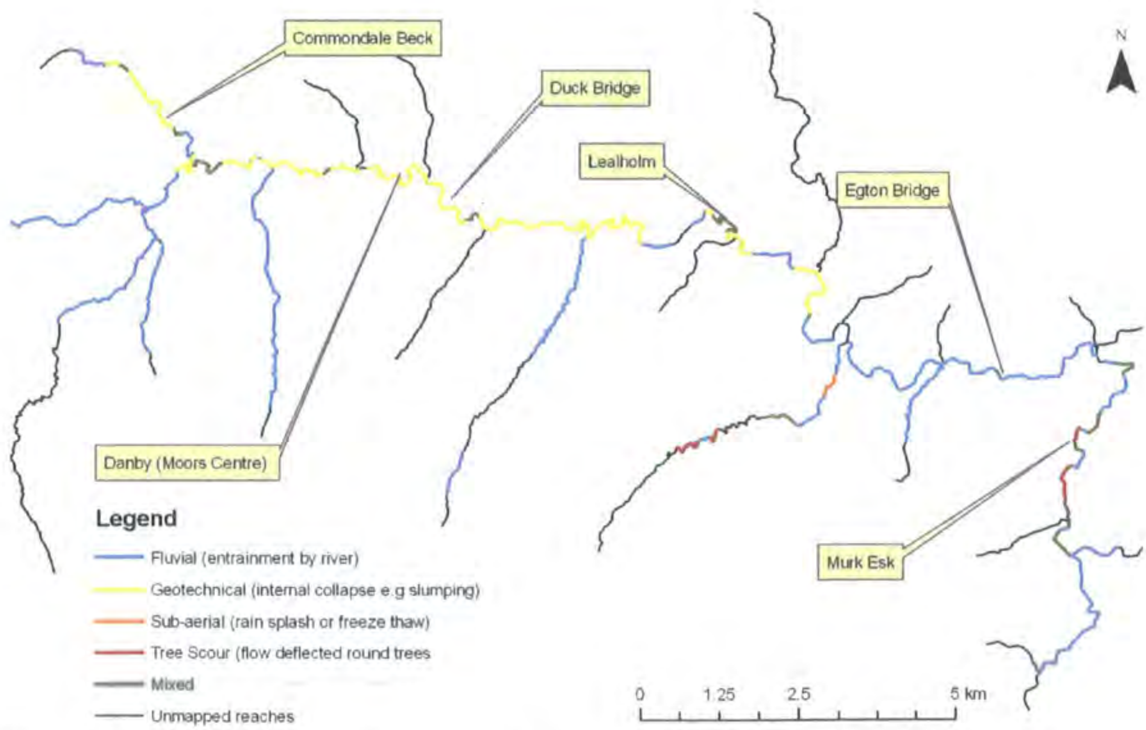


Figure 6.11: River line map illustrating dominant type of erosion

Geotechnical failures were found to be the dominant form of erosion for most of the main Esk above Lealholm and the lower section of Commondale Beck (Figure 6.12). This, in combination with the other mapped attributes such as bank height, vegetation cover, erosion extent and field observations, suggests that the high sediment loads identified between Danby (Moors Centre) to Duck Bridge are a result of the unstable banks collapsing and depositing large amounts of material into the river. In contrast, fluvial erosion was identified as the main form of erosion for most of the tributaries and the main Esk below Lealholm. In small sections of Glaisdale Beck and the Murk Esk tree scouring was identified as the dominant erosion process (Figure 6.11).

Figure 6.12: Extensive channel bank slumping of the main Esk (near Duck Bridge)

6.4 Channel bank management

The management and maintenance of channel banks directly affects the condition of the channel and hence has a direct impact on the amount of sediment delivered to the channel from channel bank sources. Although much of the banks of the Esk are well managed, 'hotspots' of poor management were identified; particularly in the main Esk between Six Arch Bridge to Duck Bridge and parts of Great Fryup Beck and Danby Beck.

It is widely agreed that where animals have direct access to the bed and banks of the river, significant amounts of sediment can potentially be deposited in the channel through the disturbance and mobilisation of the bank material caused by livestock (Walling *et al.*, 2002). Occurrences of animal poaching were observed to be significant in Danby Beck, Great Fryup Beck and for certain sections of the Esk, especially near Six Arch Bridge (Figure 6.13). These locations are the most intensively farmed in the Esk catchment and correlate directly to the locations of highest mapped erosion extent (Figure 6.6) and areas identified as being most vulnerable to erosion (Figure 6.10). This combination of observations suggest that the land use management practices in the riparian zone and river banks of the main Esk in these areas are exacerbating fine sediment inputs to the Esk.

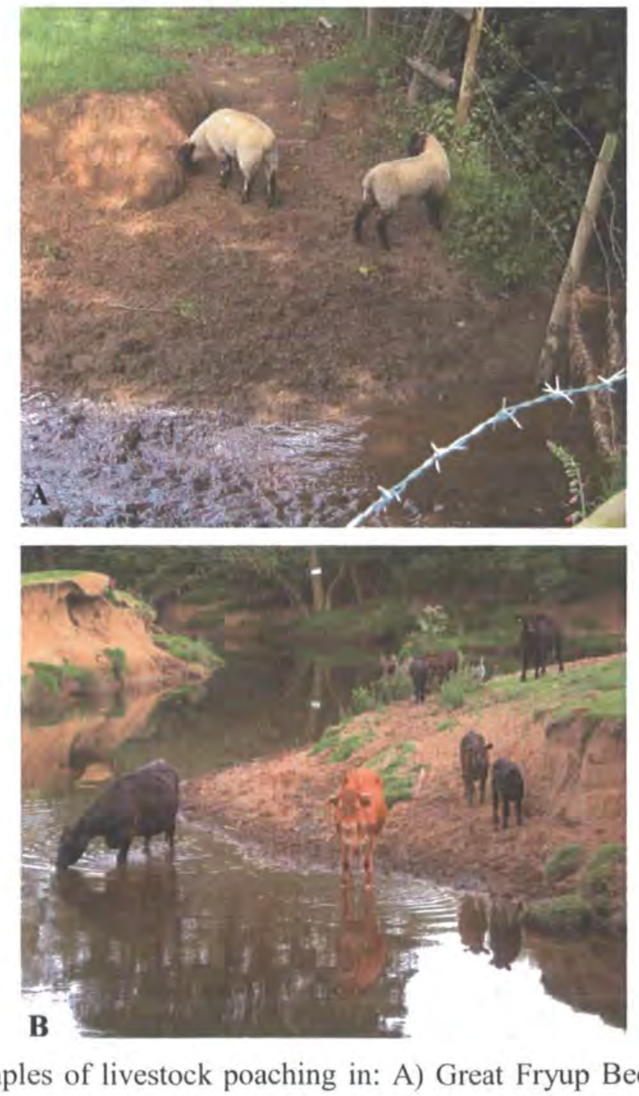


Figure 6.13: Examples of livestock poaching in: A) Great Fryup Beck: and B) the main Esk

It was also noted for that for sections of the Esk between Six Arch Bridge to Duck Bridge, as well as Great Fryup Beck and Danby Beck, that some of the riparian fences were poorly maintained (e.g. Figure 6.14). Where these artificial structures had fallen into the channel, it is possible that a significant amount of fine sediment was also deposited. Farm fords and tracks additionally cause significant amounts of fine sediment inputs and were prevalent in much of the Upper Esk (Figure 6.15). It was also noted that burrowing animals could cause significant amounts of sediment input into the channel in the Esk. Burrowing causes destabilisation of the bank material, but can also act as conduits for channelling subsurface flow into the catchments (Imeson and Kwaad, 1976); (Figure 6.16).

Figure 6.14: Example of a poorly maintained wall in Great Fryup Beck

Figure 6.15: Example of a farm ford entering the main Esk near Danby

Figure 6.16: Example of burrowing holes in the banks of the River Esk near Danby

6.5 Significance of larger scale catchment characteristics

To ascertain the larger scale controls of a river system on spatial patterns of fine sediment flux and identify possible contributing catchment sources, it is necessary to also consider macro scale catchment variables. This section examines spatial patterns of catchment inputs, riparian land use, geology and topography of the river Esk. These larger scale influences can then be compared to spatial patterns of fine sediment flux to establish the role of catchment sediment sources.

6.5.1 Catchment inputs

Catchment inputs consider the possible contributions of fine sediment from larger scale sediment sources; hence indicate the significance of catchment sources in contributing sediment to the River Esk system and the extent of hillslope-channel connectivity. Inputs of fine sediment were examined by mapping the occurrence of dominant catchment inputs, which were defined as drains, tributaries and saturated runoff. To illustrate the spatial distribution of these catchment inputs, the frequency of each was summed and divided by the length of each reach to produce a density of catchment inputs per km (Figure 6.17).

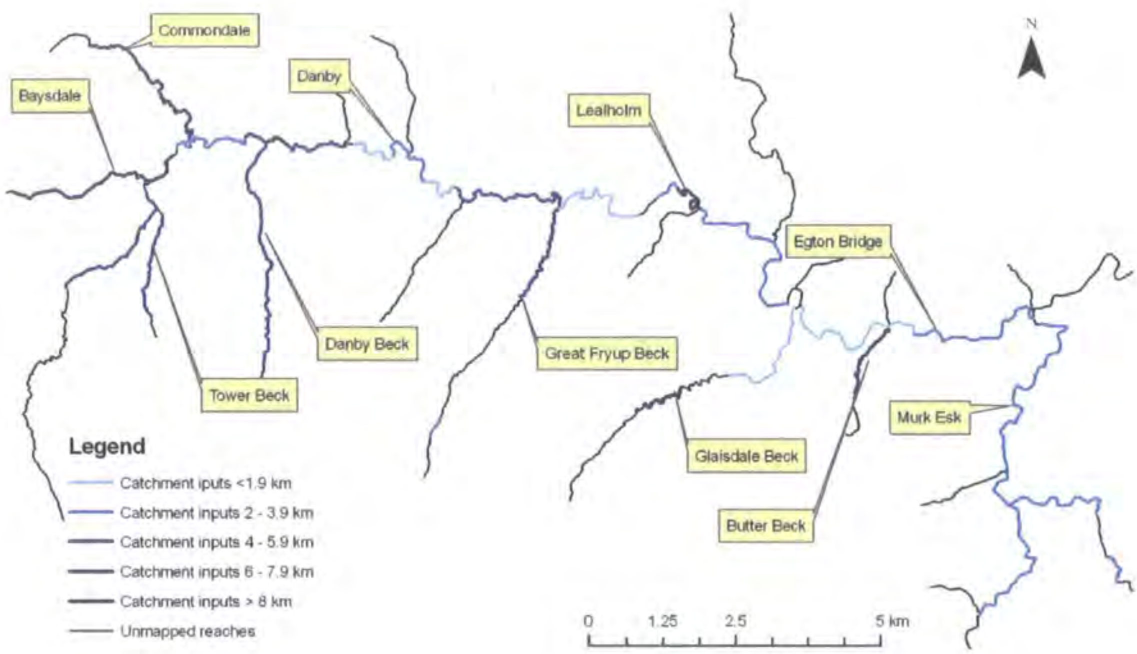


Figure 6.17: River line map illustrating dominant catchment inputs (km) (e.g. tributaries, drains and saturated runoff)

Figure 6.17 indicates that sections of Great Fryup Beck, Danby Beck, Glaisdale Beck and Butter Beck all have high densities of catchment inputs as well as high sediment fluxes (Figure 5.5). This would suggest that the hillslope to river connectivity in these tributaries is high and that catchment sediment inputs are causing significant inputs at these locations. For tributaries such as Great Fryup Beck and Danby Beck, this may relate to land use management practices which, in these sub-catchments, are intensively managed.

The tributaries draining the upper section of the Esk, such as Baysdale Beck and Tower Beck were also highlighted as having a high density of catchment inputs. However, since the sediment fluxes in these tributaries are low (Figure 5.5) this would suggest that these inputs are not significant in terms of fine sediment supply. Additionally, on the days when these headwater tributaries were mapped it had been snowing and was raining heavily; therefore it is probable that some of the identified saturated runoff was a result of weather conditions rather than permanent catchment inputs (Figure 6.18).

Figure 6.18: Saturated runoff due to heavy rain and snow melt at Tower Beck

In contrast, the catchment input densities near Danby on the main Esk are relatively low (Figure 6.17), providing further evidence that the high sediment fluxes observed here are predominantly due to local channel bank sources rather than wider catchment sources. However it must also be noted that these observations of input densities are highly dependent on the visibility of the banks and riparian zones, the weather condition and season the fieldwork was carried out. Although, this bias was greatly minimised by undertaking the fieldwork within one week allowing better consistency of field and channel conditions between the surveyed reach. Furthermore, these results doe not take into account the affect of subsurface flow which could also produce significant sediment inputs.

6.5.2 Land use of the riparian zone

Land use is a highly complex variable, but was mapped by classifying the dominant land use adjacent to the section of bank surveyed as either moorland; pasture; woodland; railways and roads; and parks and gardens (Figure 6.19). Much of the land use upstream of Glaisdale is dominated by pasture, apart from small pockets of woodland. Long stretches of pasture are particularly dominant in the River Esk riparian zone above Leaholm, which correlates with poor bank management associated with agricultural practices in these areas

(Section 6.4). Most of Baysdale Beck is dominated by moorland; the low intensity nature of this land use is portrayed in the low sediment fluxes (Figure 5.5). In contrast, much of the land use below Egton Bridge and the bottom section of Glaisdale Beck is dominated by woodland, resulting in high stability, well vegetated banks (Section 6.2).

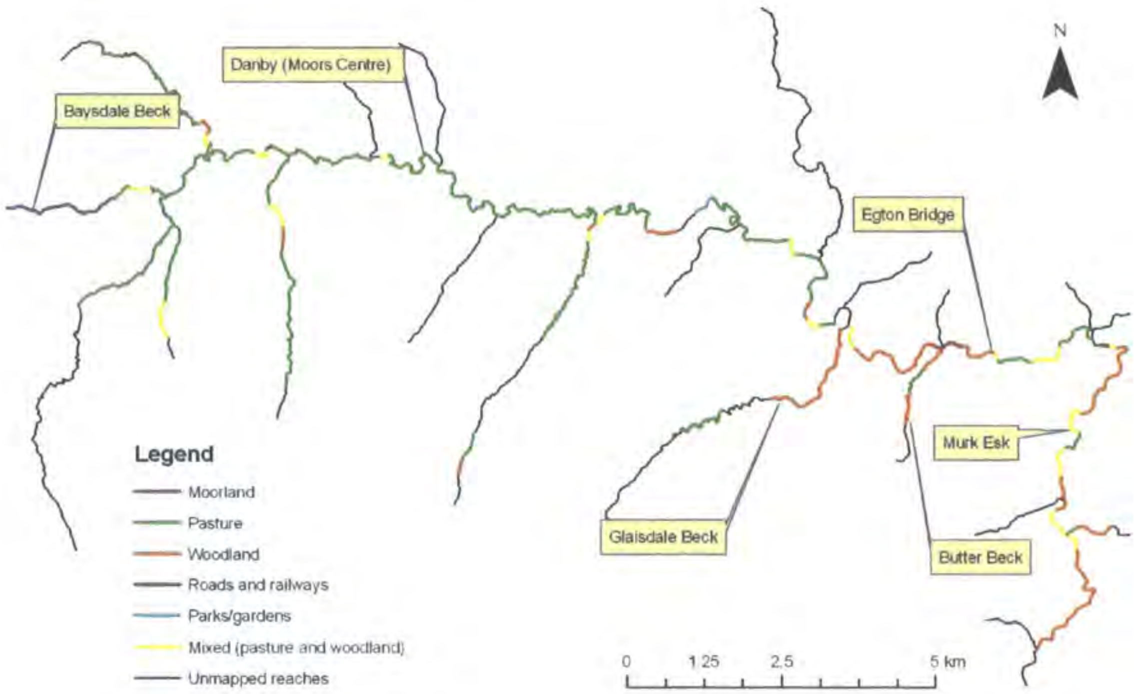


Figure 6.19: Line map illustrating dominant land use adjacent to channel banks

Figure 6.19 only provides a basic overview of the riparian zone land use and to investigate land use management practices and spatial patterns in fine sediment supply more thoroughly, a more detailed land use map would be required which encompasses the whole catchment. For better links to be made between spatial and temporal patterns of fine sediment flux, the intensity and seasonal trends of land use would also need to be considered.

6.5.3 Slope

The gradient of the channel slope and adjacent hillslopes is an important consideration when examining spatial patterns of sediment transfer because it partly governs the rate at which fine sediment is eroded transported and deposited in a catchment. Land elevation of the Esk catchment was analysed using contour data from Edina: Digimap which was then converted into a DEM using the spatial analyst tool in ArcMap. Change in land elevation (m) was then illustrated using a graded colour scale where the darker shades represent the higher land elevations.

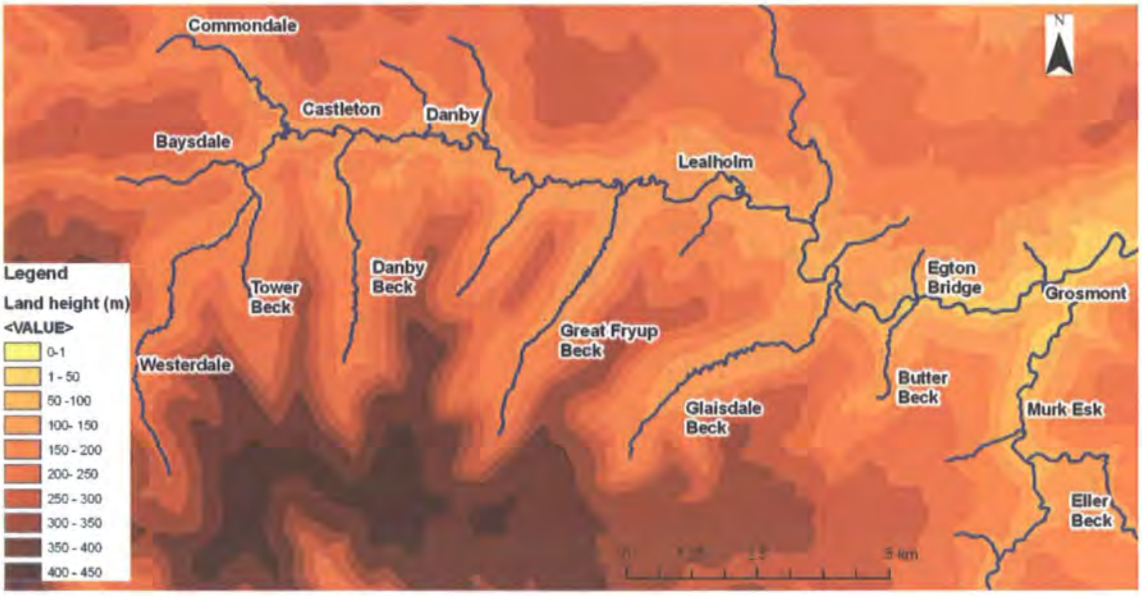


Figure 6.20: Land elevation (m) of the Esk catchment

Figure 6.20 clearly shows that the elevation of the land draining the southern tributaries, such as Westerdale, Tower Beck, Danby Beck, Great Fryup Beck and Glaisdale Beck is higher in comparison to the land draining the tributaries to the East such as Murk Esk, West Beck and Eller Beck. The higher elevations of the sub-catchments in the south west suggests that they will have a comparatively flashier response to storms, providing additional confirmation of the high catchment inputs identified in Tower Beck, Danby Beck and Great Fryup Beck (Figure 6.18).

Slope can also be examined in more detail by converting these land elevations (m) into slope gradients (percentage change in elevation) (Figure 6.21). Figure 6.21 demonstrates that although the elevation of the Westerdale, Tower Beck and Danby Beck sub-catchments is high, in comparison to Great Fryup Beck and Glaisdale Beck, the gradient of the hillslopes in these catchment is not quite as steep. This implies that in terms of sediment mobility and input, it is the gradient of the slope rather than the elevation of the land that is of more importance.

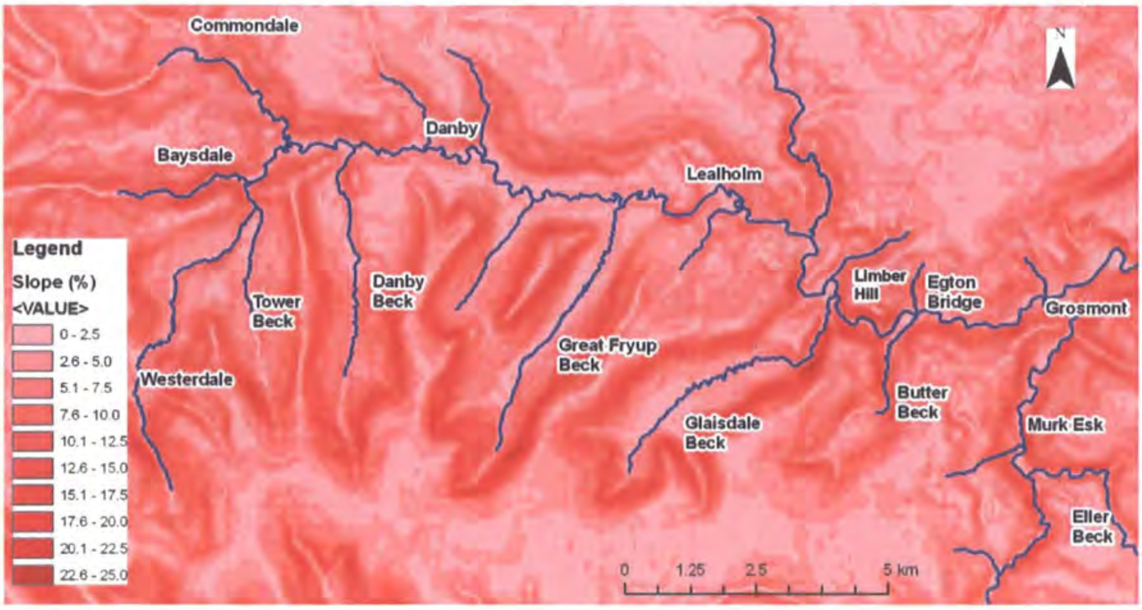


Figure 6.21: Slope map (%) for the Esk catchment

Interestingly the slope gradient on the main Esk above Egton Bridge, below the mouth of Glaisdale Beck at Limber Hill, is quite steep, after which it becomes gentler around Egton Bridge. This adds further weight to the theory that the large amounts of sediment loads observed in the section of the main Esk near Egton is a result of material being supplied by the high yielding tributaries Glaisdale Beck and Butter Beck, which is then deposited on the bed as a result of the change to the gentler gradients at Egton.

One anomaly is Butter Beck which appears to drain a catchment that has relatively low elevation and slope gradients yet also displays large sediment flux (Figure 5.5). Other catchment controls such as the underlying geology (Section 6.4.4) and catchment management practices (explored in greater detail in Chapter 8) are significant in this subcatchment.

6.5.4 Geology

The geology of the catchment has a large influence on the nature of the substrate being eroded, but also the geomorphology of the channels. Geology and lithology exert a strong control over suspended sediment since they govern the extent to which sediment can be eroded (i.e. the degree of consolidation and cohesiveness) and the ease with which it can be transported (i.e. grain size, shape and density). Due to its glacial history, the Esk catchment has an interesting spatial distribution of drift (Figure 6.22).

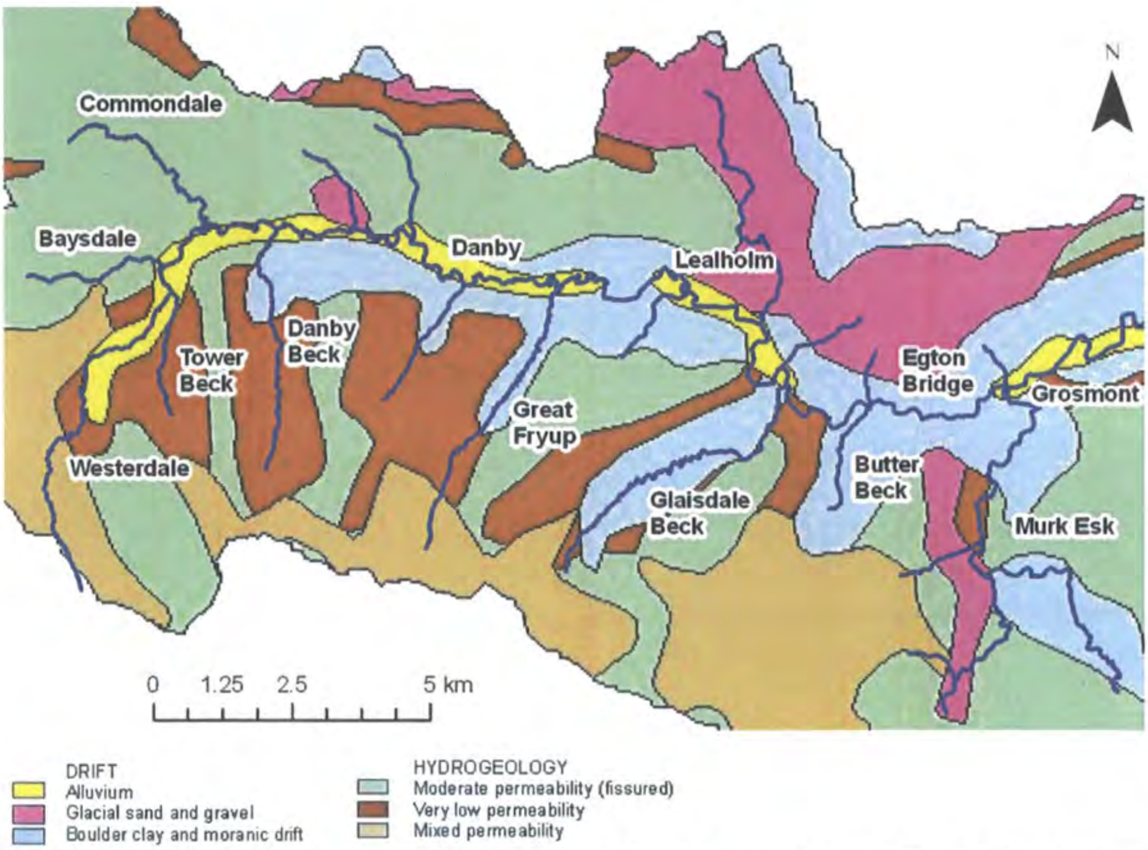


Figure 6.22: Drift geology map for the river Esk catchment (Source: The National River Flow Archive, 2001)

A division in the geology above and below Lealolm is noted. Above Lealholm the River Esk incises sandy alluvium drift. Sandy material is more easily eroded as it is poorly consolidated and less stable. This provides further evidence for the hypothesis that the large sediment fluxes observed in the main Esk near Danby are the result of local channel bank supply. In general the steep headwater tributaries above Lealholm drain through a very low and moderately permeable, hard sandstone geology, which is less easily eroded, providing explanation for low suspended sediment loads here, despite their steep subcatchment.

Below Leaholm however, the geology of the main Esk is dominated by boulder clay and moronic drift geology. Tributaries such as Glaisdale Beck, lower sections of Great Fryup Beck, Butter Beck and the Murk Esk have also been incised through reworked glacial sands and boulder clay deposits. Since glacial deposits are softer and more easily eroded than solid geology, this suggests that the underlying geology is the dominant catchment control on the high suspended sediment loads, rather than channel banks sources at Egton.

6.6 Chapter summary

This chapter shows that the two 'hotspots' in fine sediment supply identified in Chapter 5, have distinct channel and catchment characteristics governing sediment supply at these locations. The fine sediment 'hotspot' at Danby (Moors Centre) is characterised as having high, sandy, poorly vegetated banks, which are influenced by intensive agricultural management practices such as poaching, causing extensive bank slumping. This provides evidence that it is the local channel bank sources that are the dominant contributors to the high sediment fluxes observed. In contrast, the dominance of wider catchment sources in contributing sediment to the area between between Glaisdale and Grosmont in the River Esk, is demonstrated. Here stable, well vegetated channel banks exhibit little signs of erosion. Instead, a high degree of hillslope to channel connectivity in the local tributaries (Great Fryup Beck, Glaisdale Beck and Butter Beck), together with a softer, easily erodible boulder clay drift geology, suggests wider catchment sources dominantly contributed to the sediment flux.

Chapter Seven: SEDIMENT SOURCES

7.1 Overview

This chapter acts as a pilot study, examining the potential of several different approaches that can be used to infer the dominant sediment sources contributing to the two main 'hotspots' of fine sediment supply in the main Esk: 1) From Danby (Moors Centre) to Duck Bridge and: 2) from Glaisdale to Grosmont. Based on the spatial and temporal patterns in fine sediment flux (Chapter 5) and channel mapping observations (Chapter 6), it is hypothesised that the dominant sediment source contributing to the high yields of sediment near Danby is as a result of local bank collapses. In contrast, from Glaisdale to Grosmont it is hypothesised high sediment fluxes were contributed by wider catchment sources, supplied by the high yielding tributaries (Butter Beck, Glaisdale Beck and to some extent, Great Fryup Beck), which drain into this section of the main Esk. The purpose of this chapter is to validate these suggestions by analysing the material deposited in the TIMS samplers.

To test these hypotheses sediment characteristics of source samples (collected from channel banks and riparian zones) were compared to that of the suspended sediment samples retained in the TIMS. To facilitate this, catchment sediment source samples and TIMS suspended sediment samples were split into six spatial groupings (Figure 7.1):

1) **Channel sources (Non-TIMS)** - Channel bank source samples collected from the main Esk (to give an indication of the significance of channel bank in supplying fine sediment to the Esk);
2) **Catchment sources (Non-TIMS)** - Source samples collected from riparian zones adjacent to the channel bank throughout the River Esk catchment (to give an indication of the importance of catchment sources in contributing fine sediment);

3) **TIMS tributaries (above Duck Bridge)** - Suspended bulk material retained from the TIMS deployed in the tributaries above Duck Bridge (Commondale Beck, Baysdale Beck, Westerdale Beck, Tower Beck and Danby Beck);
4) **TIMS tributaries (below Duck Bridge)** - Suspended bulk material retained from the TIMS deployed in the tributaries below Duck Bridge (Great Fryup Beck, Glaisdale Beck, Butter Beck, Eller Beck and West Beck).
5) **TIMS main Esk (Duck Bridge and above)** - Suspended bulk material retained from the TIMS deployed in the main Esk above Duck Bridge (Six Arch Bridge, Danby A and Danby B and Duck Bridge);
6) **TIMS main Esk (below Duck Bridge)** - Suspended bulk material retained from the TIMS deployed in the main Esk below Duck Bridge (Lealholm, Glaisdale, Egton Bridge and Grosmont).

(N.B The names in bold shall be referred to when making reference to these spatial groupings throughout the rest of the chapter).

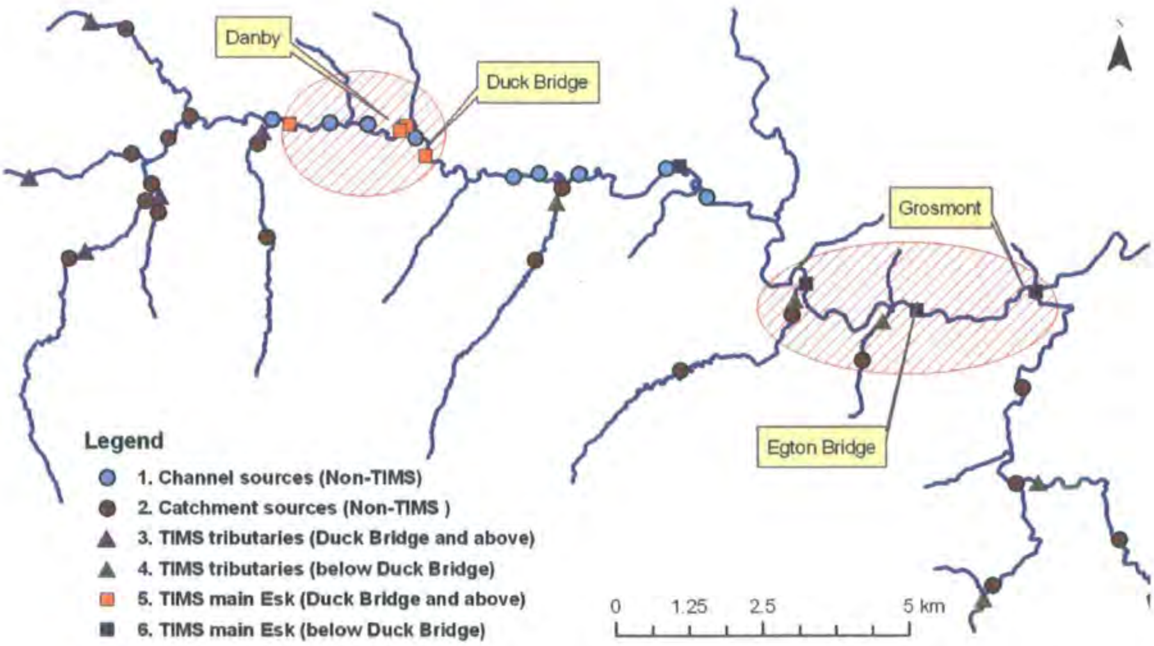


Figure 7.1: Spatial groupings of channel and catchment (Non-TIMS) source samples and TIMS samples (tributaries above and below Duck Bridge and main Esk above and below Duck Bridge).

To infer the dominant sediment sources in the two sediment 'hotspot' locations in the Esk catchment, the sediment characteristics particle size; sediment colour; magnetic susceptibility; and metal content were measured on both the suspended sediment and sediment source samples. These measured properties have been critically assessed to determine their potential as fingerprints of the dominant sediment sources in the Esk catchment (Section 7.2 – 7.4).

7.2 Fine sediment characteristics

7.2.1 Particle size

Using Gradistat (Blott and Pye, 2001), the median particle size (D_{50}) of the bulk samples retained from the TIMS were measured. D_{50} represents the diameter for which 50% of particles in the sample are smaller and are displayed using box plots (Figure 7.2).

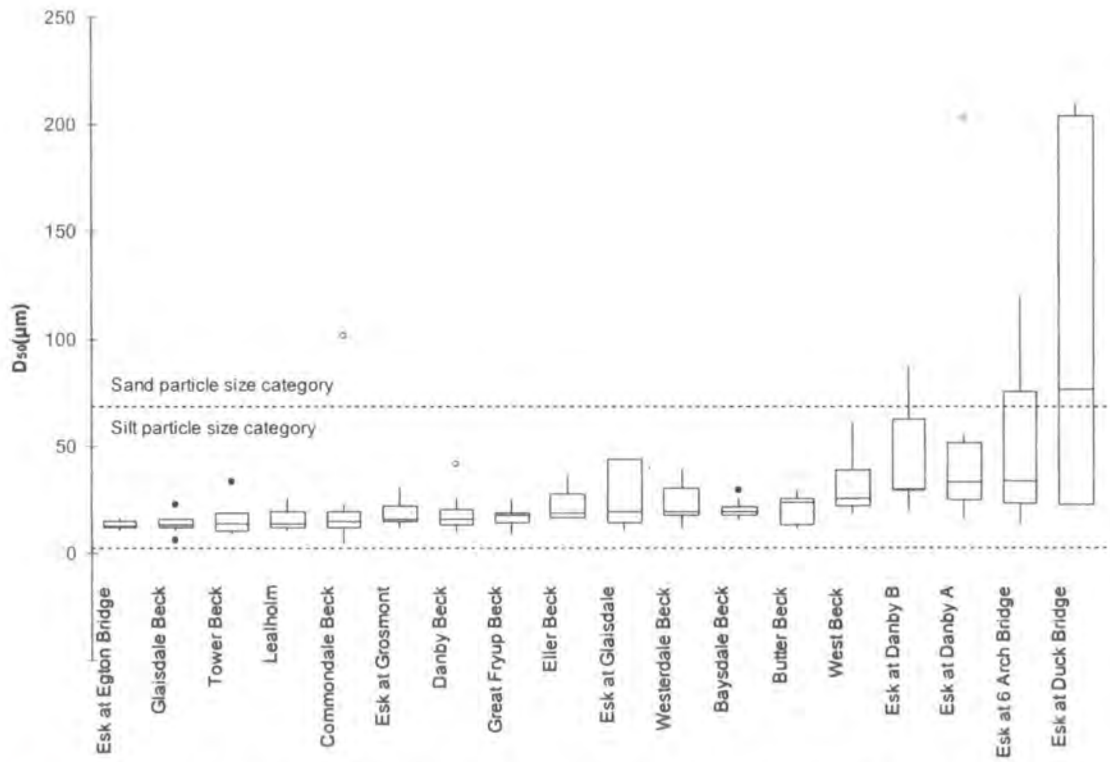


Figure 7.2: Box plots of median particle size accumulated in the TIMS, ordered by median D_{50} (μm), dashed line indicates sand (>62.50 μm) and silt particle size categories (3.90 μm - 62.50 μm)

Most of the sediment trapped in the TIMS was of fine silt particle size (3.90 μm – 62.50 μm). The coarsest particles were found at Duck Bridge, Danby and Six Arch Bridge on the main Esk (104 μm; 55 μm; and 47 μm respectively); which are also areas identified as having high levels sediment flux (Figure 5.5). Some of the material retained at Duck Bridge falls into the sand particle size category (>62.50 μm). In contrast, the finest material was collected at Egton Bridge, Glaisdale Beck and Great Fryup Beck (14 μm; 14 μm; and 15 μm respectively); these areas were also highlighted as zones of high sediment flux (Figure 5.5). The large variation in grain size of the material collected from Danby (Moors Centre) and Egton suggests that these two 'hotspot' locations are predominantly sourced from different areas in the catchment. Figure 7.2 also shows an increase in variability in particle size as the median D_{50} increases. This could be indicative of variable source areas and pathways with different flow conditions.

The D_{50} of the sediment source samples were also measured and were compared spatially with the grain size of the material retained in the TIMS. This was done using coloured proportional circles, which indicated the six spatial groupings (Figure 7.1), on a River Esk map (Figure 7.3). The grain size of the sediment source samples are significantly larger than that of the TIMS fluvial material. This is expected due to the effect of physical and chemical alterations during transport, which markedly reduces the particle size of the suspended sediment. Figure 7.3 again highlights the coarsest TIMS material was trapped in the samplers deployed in the main Esk upstream of Duck Bridge. This correlates to the coarse sediment source material collected from the River Esk channel banks, supporting the inferred significance of the local, predominantly sand channel bank sources as the dominant sediment supply near Danby. Given these larger particle sizes, once the material has been deposited as a result of channel bank failures it is unlikely to be transported long distances until high flow events. In addition, the fact that this coarse sediment is not evident further downstream below Duck Bridge implies that large amounts of coarser material are being deposited and stored between Danby and Duck Bridge on the main Esk, further supporting the field observations (Chapter 6).

The catchment samples collected from Butter Beck and Glaisdale Beck sub-catchments are finer in comparison (33 μm and 100 μm respectively). This is indicative of the reworked finer boulder clay drift geology present in these sub-catchments (Figure 6.22). Moreover, this fine catchments source material correlates with the smaller grain sizes of the material retained in the TIMS samplers deployed in the tributaries Glaisdale Beck and Butter Beck (14 μm and 19 μm respectively), and with the suspended material collected at Glaisdale and Egton Bridge (23 μm and 14 μm respectively). This provides further confirmation supporting the hypothesis that the high sediment fluxes observed between Glaisdale and Grosmont are sourced from wider catchment locations delivered by Glaisdale Beck and Butter Beck.

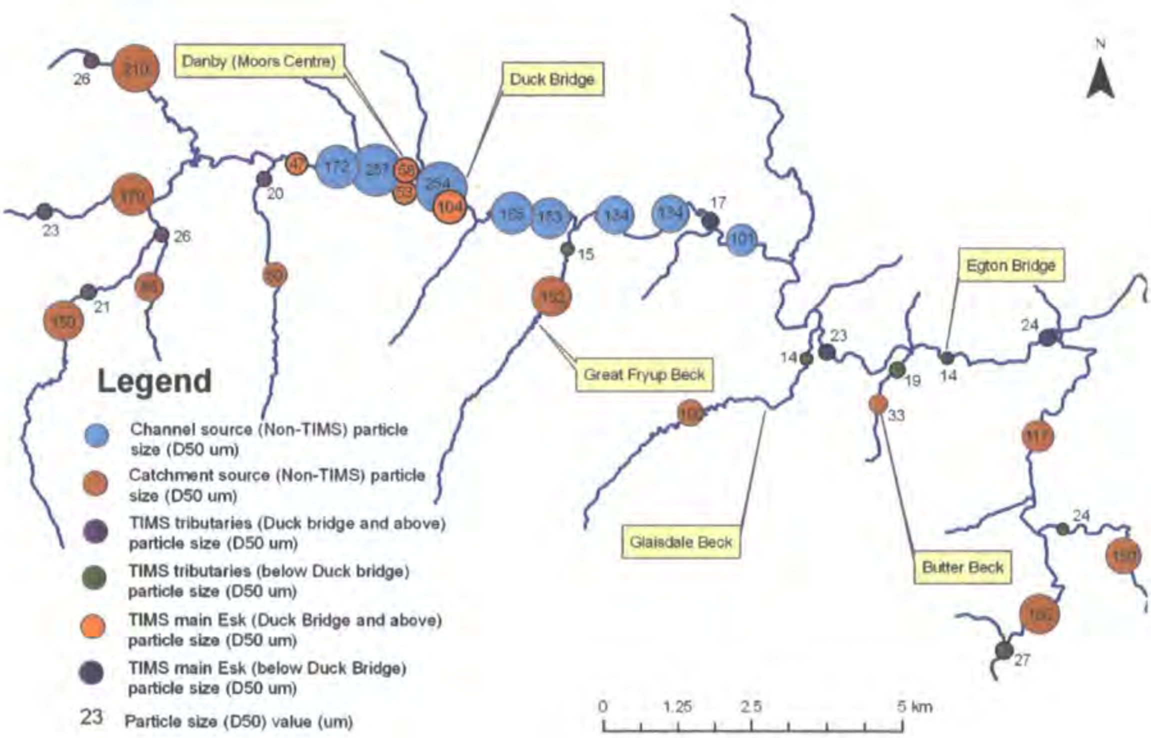


Figure 7.3: Spatial variation in mean particle size (D_{50}) (μm) of sediment retained in the main Esk TIMS (above and below Duck Bridge); tributaries TIMS (above and below Duck Bridge); and channel and catchment sources (Non-TIMS)

However the extent to which sediment sources can be inferred by comparing the particle size of suspended and sediment source samples is greatly limited since the effect of size selective transport and delivery processes has not been accounted for. This could therefore have a significant influence on the spatial distribution of grain size (Walling and Moorehead, 1989); hence conclusions drawn from the analysis of particle size should be treated with caution.

7.2.2 Sediment colour

It was further hypothesised that variation in the colour of the sediment filter residue from the mass flux bulk samples collected from the TIMS could be due to variable source areas within the Esk catchment (Figure 7.4). The colour of these filter papers were defined using Munsell® hue, value and chroma colour notations (H V/C) which were then converted into red, blue and green (rgb) values using Munsell® Conversion Software V6.5.17. By identifying the suspended sediment colour at each TIMS site for each sampling period, a detailed catalogue of sediment colour was created and used to indicate different source areas.

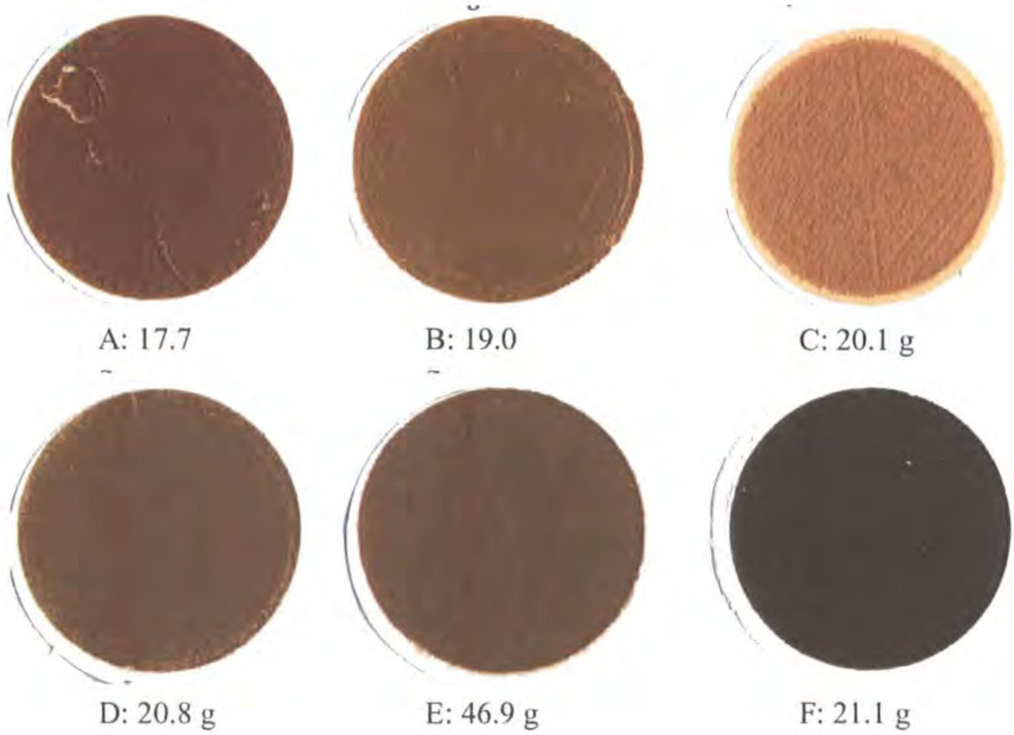


Figure 7.4: Examples of the colour variation in filtered sediment residue and their weights (g) at: A) Commondale Beck; B) Duck Bridge; C) Danby Beck; D) Egton Bridge; E) Butter Beck and F) West Beck

It was initially thought that the filtered residue sediment weight could be a complicating factor controlling the colour (Udelhoven and Symader, 1995). For example the greater the sediment weight collected on the filter paper the darker and stronger the colour created. To determine the influence of sediment weight on filter paper colour, a range of suspended sediment concentrations, using sediment from Duck Bridge, Great Fryup Beck and Butter Beck, were filtered. When the rgb colour values were compared to sediment weight for Duck Bridge, Great Fryup and Butter Beck (Figure 7.5A) it was noted that there was an initial relationship between decreasing colour value and increasing sediment weight up to approximately 15 mg. This suggests that below sediment weights of 15 mg, it is the weight of filtered residue sediment that is the dominant control on colour.

When samples with filtered residue weights of lower than 15 mg are removed, a much weaker relationship between increasing sediment weight and colour is observed (Figure 7.5B). Although this relationship is not truly flat, given the weakness of this relationship, it can be assumed that the colour of filter papers with residue weights over 15 mg are more dominantly controlled by other factors, such as variable source areas, rather than sediment weight. In light of this, colour from samples with a filtered sediment weight above 15 mg were used to examine spatial variations in suspended sediment characteristics.

A further problem encountered when using colour to determine sediment provenance, was that due to the drying and ball milling of the sediment source samples, when they were rewetted, mixed and filtered to similar concentrations as the suspended samples, the colour created on the filter paper was faint and unevenly distributed. Additionally, it was thought the colour of the river water present when filtering the TIMS samples also stained the filter paper, intensifying the colour created. Therefore the colour of the sediment source samples were not directly comparable with that of the filtered suspended sediment samples, restricting the analysis of colour to the suspended sediment material obtained in the TIMS samplers alone.

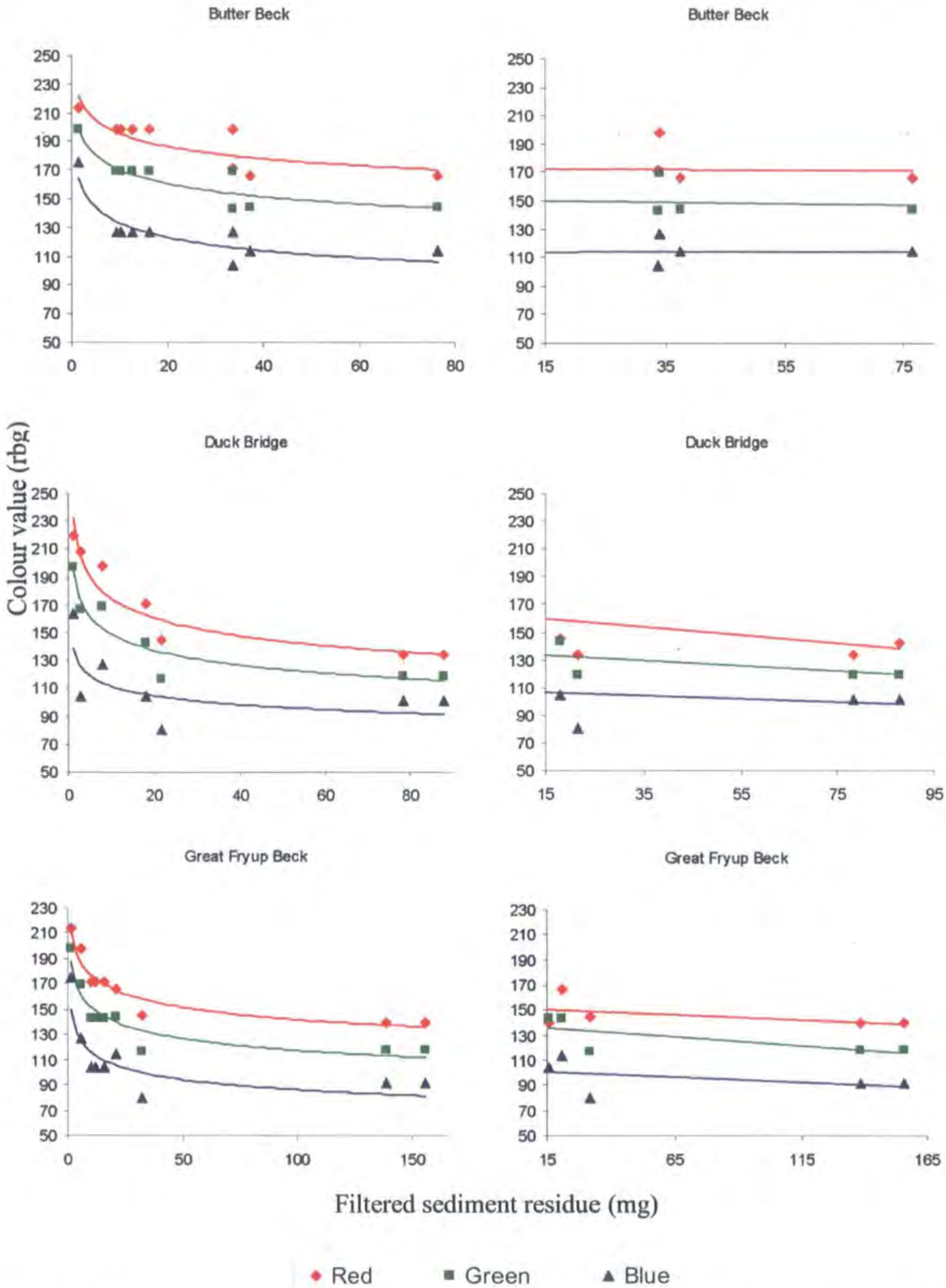


Figure 7.5: A) Relationship between colour values (rbg) for Duck Bridge, Butter Beck and Great Fryup Beck and filter residue weight (mg); B) After removing samples with filtered sediment weights below 15 mg.

Using the four spatial groupings of TIMS samples (Figure 7.1) rbg colour values of the samples which had filtered sediment residue weight of over 15 mg were plotted on to a ternary diagram (Figure 7.6).

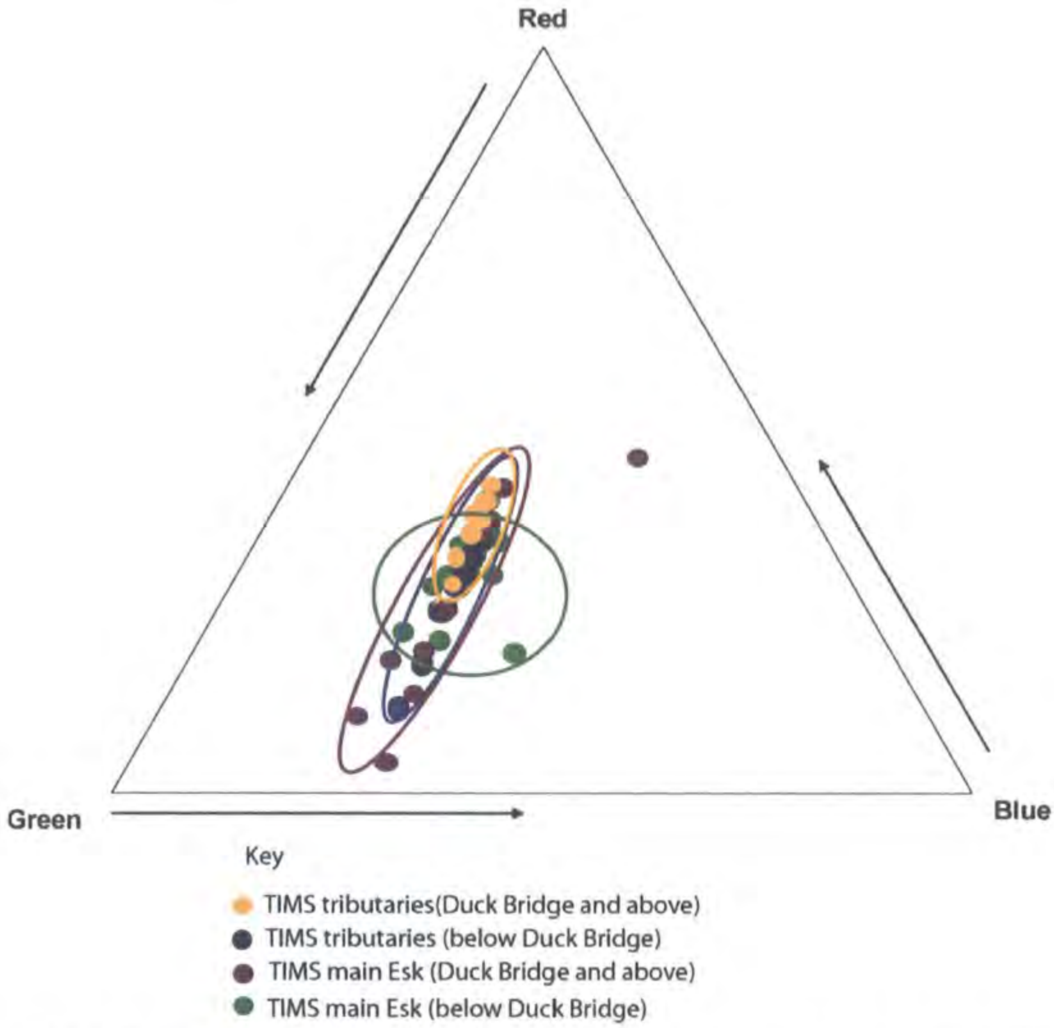


Figure 7.6: Ternary diagram showing red, blue and green (rgb) values for the four spatial groups of suspended material obtained in the TIMS (Coloured circles indicate clusters of points for each of the four spatial groups)

Figure 7.6 shows some clustering of points within each spatial group indicating consistencies in the colour of suspended sediment collected from the different sampling areas, which could be suggestive of variable contributing source areas in the catchment. However, it is hard to identify definite spatial distributions in sediment colour due to the considerable overlap between the different spatial groupings. This is to be expected given only the colour of the fluvial sediment was analysed and greatly limits the extent to which the analysis of sediment colour can be used to identify dominant source areas. In summary, for the case of the River Esk, colour defined by rbg colour values, does not have the sensitivity to allow great enough variability between the spatial groups to identify possible source areas on the basis of the suspended sediment material alone.

7.2.3 Magnetic susceptibility

The magnetic properties of suspended sediment in comparison to source samples has been widely used as a method for identifying sediment sources (e.g. Slattery *et al.*, 1995; Walden *et al.*, 1997). The volume specific high frequency magnetic susceptibility (X_{volhf}), volume specific low frequency magnetic susceptibility (X_{vollf}), mass specific high magnetic susceptibility (X_{hf}), mass specific low magnetic susceptibility (X_{lf}) and frequency dependent susceptibility ($X_{fd\%}$) magnetic parameters were measured on both the suspended sediment and source material collected in the Esk. However, only X_{lf} and $X_{fd\%}$ magnetic properties were used to identify the dominant source areas contributing to the two 'hotspot' areas, as these parameters have been found to have a better ability at discriminating source areas (Slattery *et al.*, 1995).

Particle size analysis showed that most of the material collected in the TIMS was smaller than 63 μm; therefore magnetic susceptibility analysis was only performed on source material finer than 63 μm to account for the influence of changes in particle size on magnetic properties. In any case, the relationship between particle size and magnetic properties, though complex and not well understood, is thought to have little effect on the magnetic susceptibility (Walden *et al.*, 1997).

When X_{lf} and $X_{fd\%}$ magnetic properties were compared using the six spatial groupings (Figure 7.1), although there was much scatter, some spatial clusters can be identified (Figure 7.7). These spatial clusters can be illustrated more clearly by plotting regions which envelope the spatial groupings 1 – 4 (channel and catchment sources (Non-TIMS) and TIMS tributaries samples above and below Duck Bridge) only displaying the means for each group (Figure 7.8). These shaded envelopes can then be compared with the magnetic properties of the material collected in the TIMS deployed in the main Esk above Duck Bridge (Figure 7.8A) and below Duck Bridge (Figure 7.8B), with the aim of identifying links between dominant source areas and the two 'hotspots' in suspended sediment in the River Esk.

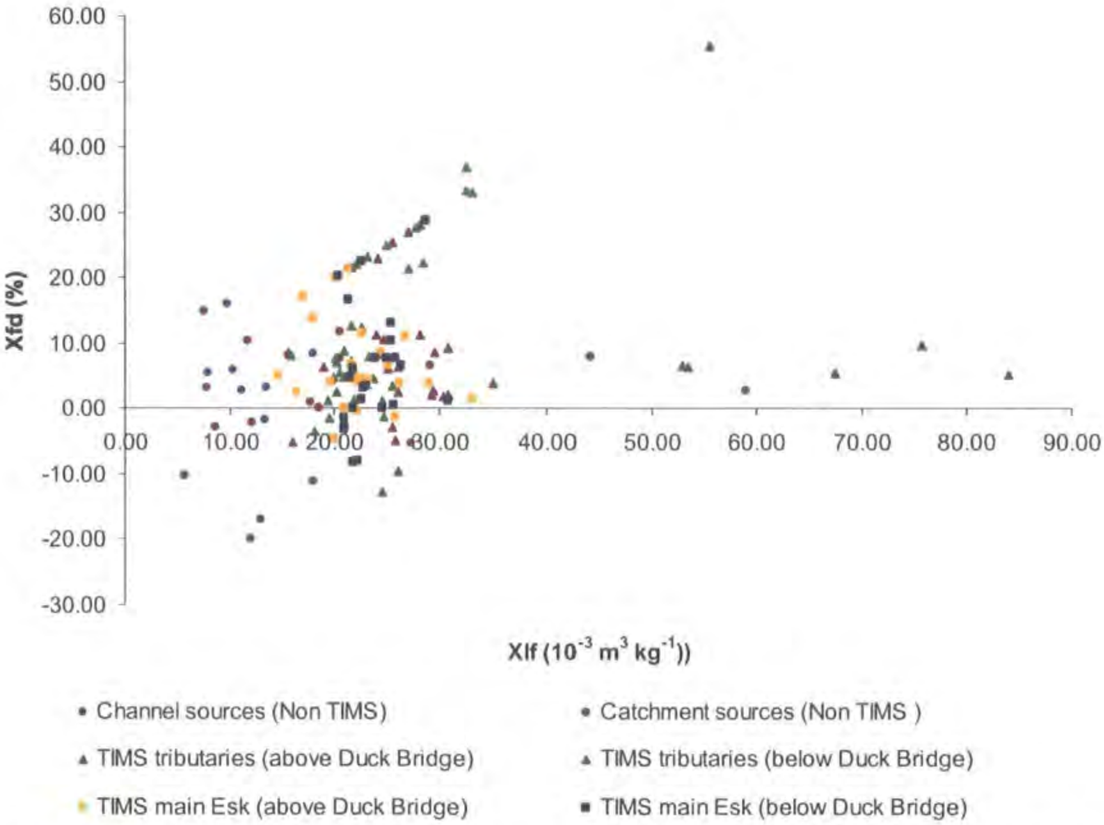


Figure 7.7: X_{lf} and $X_{fd\%}$ for channel and catchment (Non-TIMS) source samples; TIMS tributaries (above and below Duck Bridge) and TIMS main Esk (above and below Duck Bridge) samples

Figure 7.8A suggests that the headwater tributaries draining into Danby are not dominant sediment sources contributing to high sediment fluxes, due to the poor correlation in magnetic properties of suspended material collected for the tributaries above Duck Bridge with that of the suspended material collected in the main Esk. In contrast, the magnetic properties of the channel and catchment (Non-TIMS) source samples overlie that of the TIMS samples (main Esk above Duck Bridge); this similarity therefore suggests that these are dominant sediment sources contributing to fine sediment at these locations.

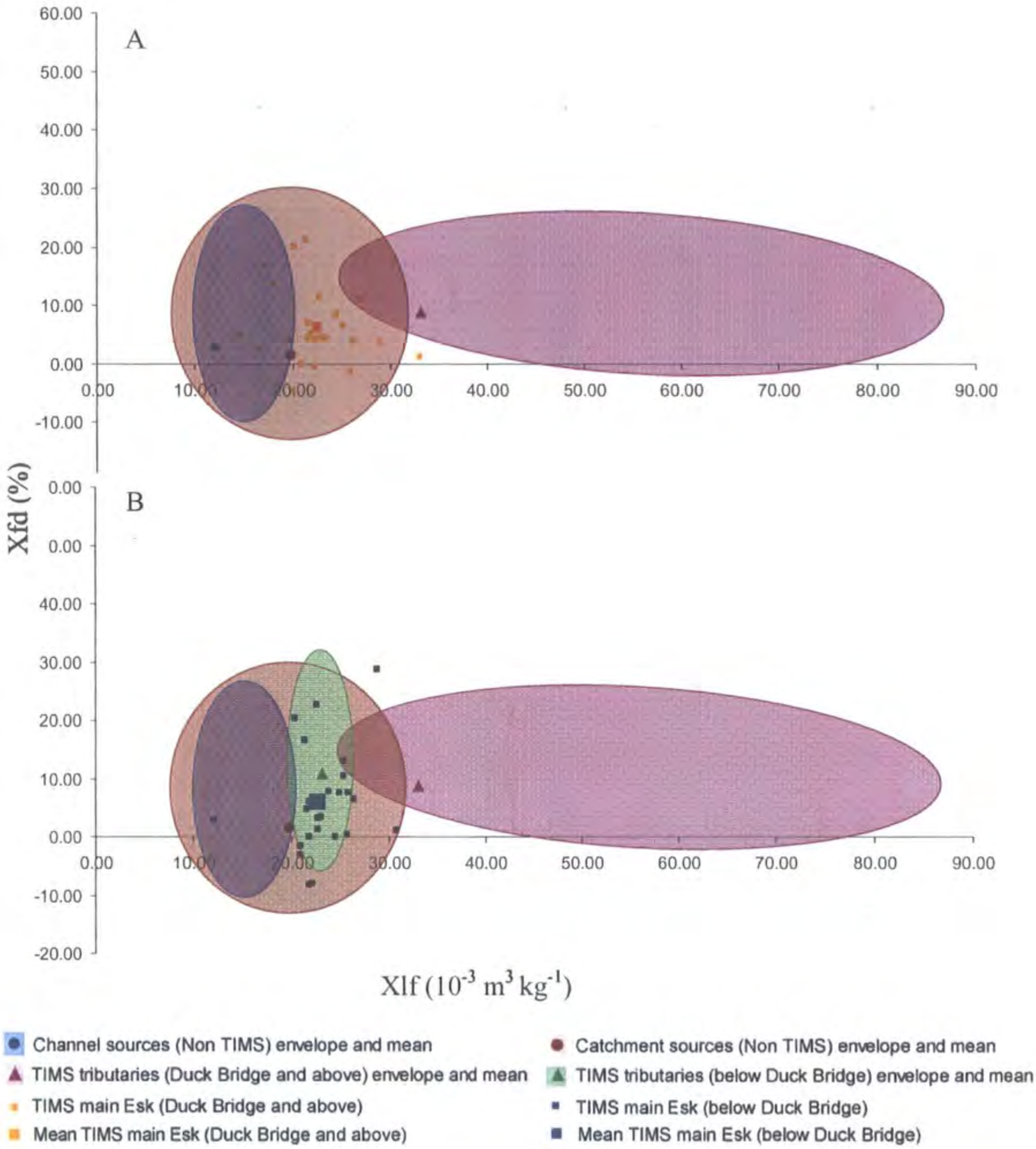


Figure 7.8: X_{lf} and $X_{fd\%}$ for: A) TIMS (Duck Bridge and above): and B) TIMS (below Duck Bridge), with mean X_{lf} and $X_{fd\%}$ for TIMS tributaries (above and below Duck Bridge) and channel and catchment (Non-TIMS) source samples

To work out the specific proportions of channel and catchment sources contributing to the high suspended sediment yields at Danby, an 'unmixing' model, similar to that used by Walden *et al*. (1997), can be used (Walling, 2005). However, since the two source areas have such similar magnetic properties, in numerical terms, it is not possible to 'unmix' the suspended sediment on the basis of these two sources material types alone. This highlights a limitation of the 'unmixing' model and can be minimized in future by collecting more source samples from source locations that better represent the dominant sediment source areas, or by using other parameters, such as metal concentrations (Section 7.3), which may produce increased variability between source areas.

Figure 7.8B suggests that the headwater tributaries do not significantly supply fine sediment to the main Esk (below Duck Bridge) due to the dissimilarity of magnetic properties between TIMS tributaries (above Duck Bridge) material and TIMS main Esk (below Duck Bridge) material. However, Figure 7.8B highlights the dominance of the tributaries that drain into the lower main Esk since the magnetic properties of the suspended sediment retained in these tributaries (such as Glaisdale Beck and Butter) are similar to that of the TIMS main Esk (below Duck Bridge) material. The magnetic properties for the catchment sources (Non-TIMS) are also similar to that of the TIMS main Esk (below Duck Bridge) samples, which would be expected as field observations suggest that Glaisdale Beck and Butter Beck are predominantly sources by their sub-catchments.

Again, as the magnetic properties of the catchment sources (Non-TIMS) and TIMS tributaries samples (below Duck Bridge) are so similar, it is not possible to identify more accurate proportions of each supplying the main Esk using an 'unmixing' model. Yet, since the majority of the magnetic properties for the TIMS main Esk samples (below Duck Bridge) cluster in the green shaded envelope (representing the magnetic properties of the TIMS tributaries (below Duck Bridge)), suggests the dominance of these tributaries in contributing to the sediment loads at this 'hotspot' in supply.

To summarise, magnetic susceptibility has the potential of fingerprinting dominant sediment sources in the River Esk catchment, but due to similarity in magnetic properties of the suspended sediment and source samples, its was not possible to provide more quantitative estimations of source areas contributions use an 'unmixing' model.

7.2.4 Metals

Metal concentrations of the source and suspended sediment material can also be used to discriminate potential sources. Before sediment sources can be ascribed using these geochemical signatures, the control of the particle size distribution of eroded and transported sediment must be accounted for as this may influence the relationship found between suspended sediment samples and source samples. In order to correct for these effects, the measured particle size distribution of both the sediment source and suspended sediment samples were used, to estimate the particle specific surface area (SSA (m^2 mm^{-3})), assuming that the particles are spherical (Gruszowski *et al.*, 2003).

The SSA results were highly variable, so individual SSA results were standardised to SSA of 0.1 m^2 mm^{-3}. Individual particle sizes for each metal concentration were then accounted for using the following equation:

$$C_{sm} = C_{so}\left(\frac{0.1}{SSAs}\right) \qquad (7.1)$$

Where: C_{sm} = particle size corrected concentration of metal m in sample s

C_{so} = original concentration of metal m in sample s

SSAs = specific surface area of sample s (assuming the particles are spherical).

Following previously published studies (Walling, 2005; Phillips *et al.*, 2001) concentrations of five heavy metals were examined in more detail: aluminium (Al), potassium (K), manganese (Mn), Lead (Pb) and Iron (Fe). To provide a broad overview of which out of the selected metal concentration distribution allow the best discrimination between suspended sediment and source areas, all five of the selected metals were compared with each other using a series of scatter plots (Figure 7.9).

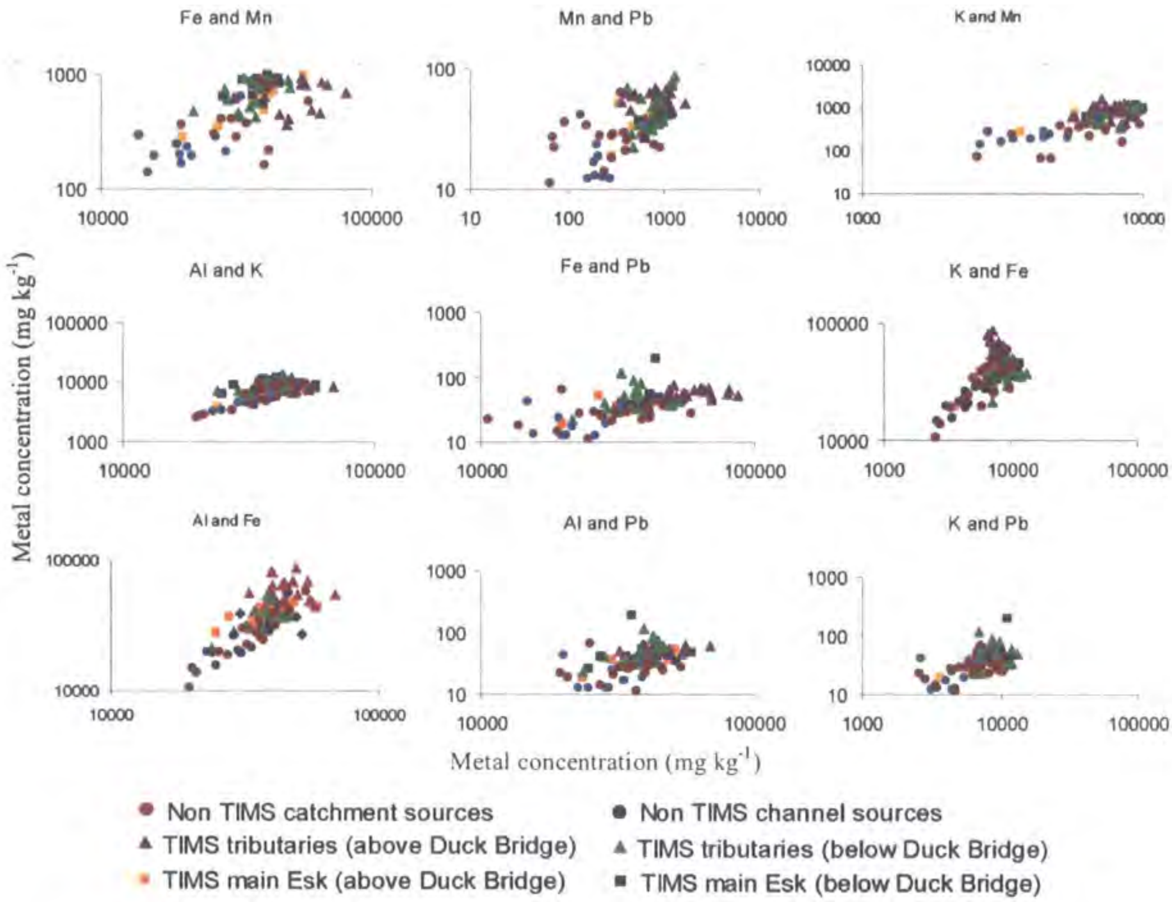


Figure 7.9: Comparison of metal concentrations (Al, Fe, Pb, K and Mn)

Fe and Pb concentrations appeared to show strong spatial clustering between source areas and TIMS material so were examined in more detail. This was done again using shaded envelopes to indicate the distribution of metal concentrations for the same spatial groupings 1 - 4 (as used in section 7.2.3) in comparison to the metal properties of TIMS material collected from the main Esk above Duck Bridge (Figure 7.10A) and below Duck Bridge (Figure 7.10B). The metal values for the main Esk above Duck Bridge indicate that dominant sediment sources contributing to the high sediment fluxes are a mixture of channel and catchment sources due to the observed similarities in metal concentrations (Figure 7.10A). This agrees with the findings of the magnetic susceptibility (Section 7.2.3).

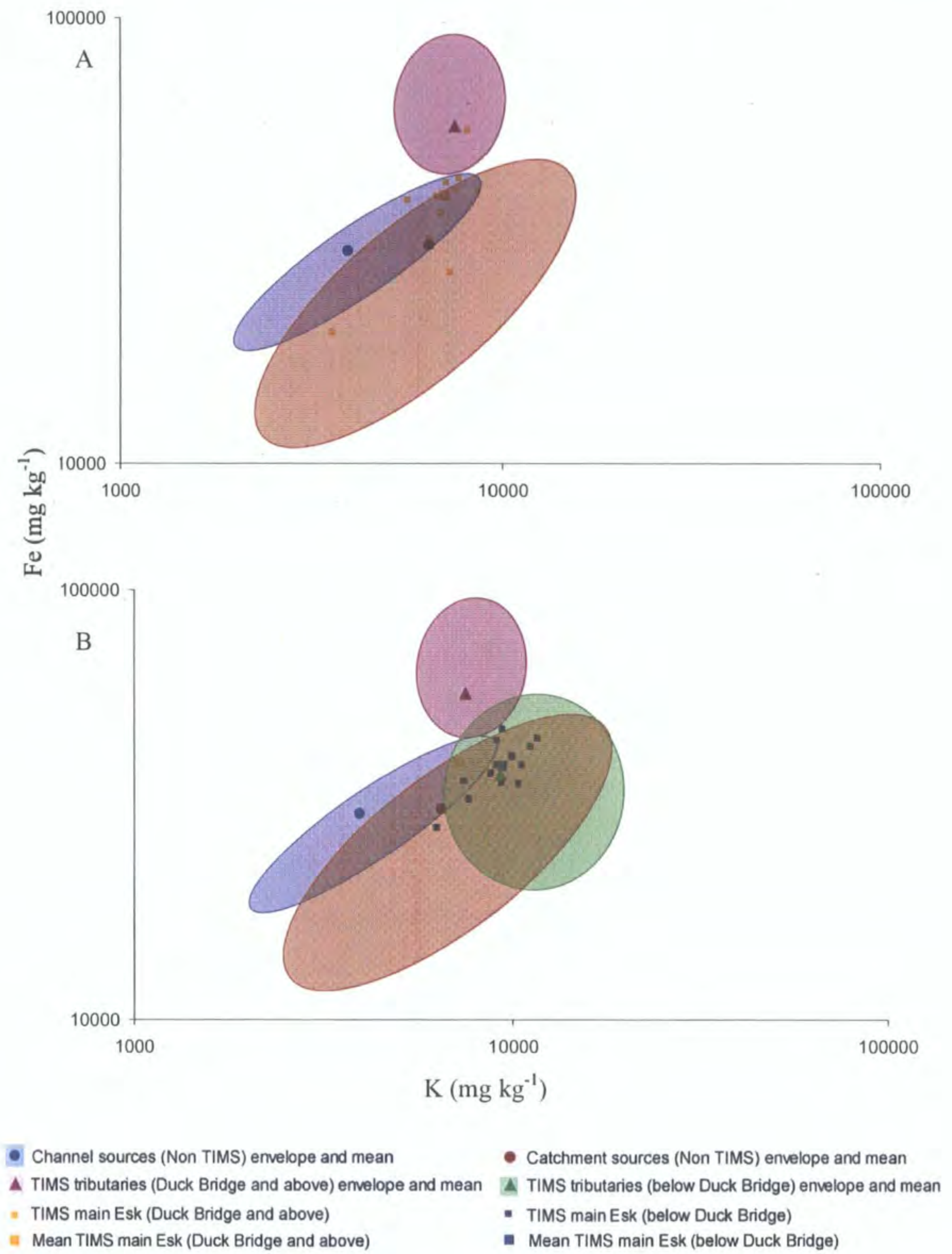


Figure 7.10: Comparison of K and Fe concentrations for: A) TIMS main Esk samples above Duck Bridge; and B) TIMS below Duck Bridge, with mean K and Fe concentrations for TIMS tributaries (above and below Duck Bridge) and channel and catchment (Non-TIMS) samples

In contrast, Figure 7.10B indicates that the majority of the TIMS main Esk samples (below Duck Bridge) have similar metal concentrations to that of the TIMS tributaries (below Duck Bridge) material, so much so that the mean Fe and K metal concentrations nearly completely overlay each other. This indicates the dominance of these tributaries (Great Fryup Beck, Glaisdale Beck and Butter Beck) in supplying sediment and again further agrees with the findings of the magnetic parameters (Section 7.2.3). Figure 7.10B also shows that the sediment supplied by the headwater tributaries above Duck Bridge are not significant contributors to the high sediment yields in the Esk catchment. As with the magnetic properties (Figure 7.8B), some of the metal values identified in the TIMS main Esk (below Duck Bridge) also falls into the catchment (Non-TIMS) source material envelope, which again is to be expected since field observations identified the significance of catchment sources contributing to the sediment supplied by the tributaries in the lower Esk.

The potential of using heavy metal properties to fingerprint dominant sediment sources is demonstrated. Although, as with the magnetic parameters, it is not numerically possible to 'unmix' these TIMS samples to estimate the specific proportions of each identified sediment source since there is not enough variation in the measured metal concentrations of the source areas.

7.2.5 Combined properties

It is widely accepted that to identify sediment sources with increased certainty, the use of multiple properties is required, allowing several potential sources to be discriminated (Collins *et al.*, 1997a; 1997b). Therefore, magnetic properties and metal content were compared together. Figure 7.11 presents results when Pb concentrations and low frequency magnetic susceptibility are compared; using the same spatial groupings outlined in Figure 7.1 and shaded envelopes as in Section 7.2.3 and 7.2.4. Figure 7.11A provides further evidence that the main Esk above Duck Bridge is sourced by a mixture of River Esk channel bank and catchment sources. Similarly, the tributaries that drain into the Esk below Duck Bridge are again highlighted as the dominant source contributing to the River Esk below Duck Bridge (Figure 7.11B).

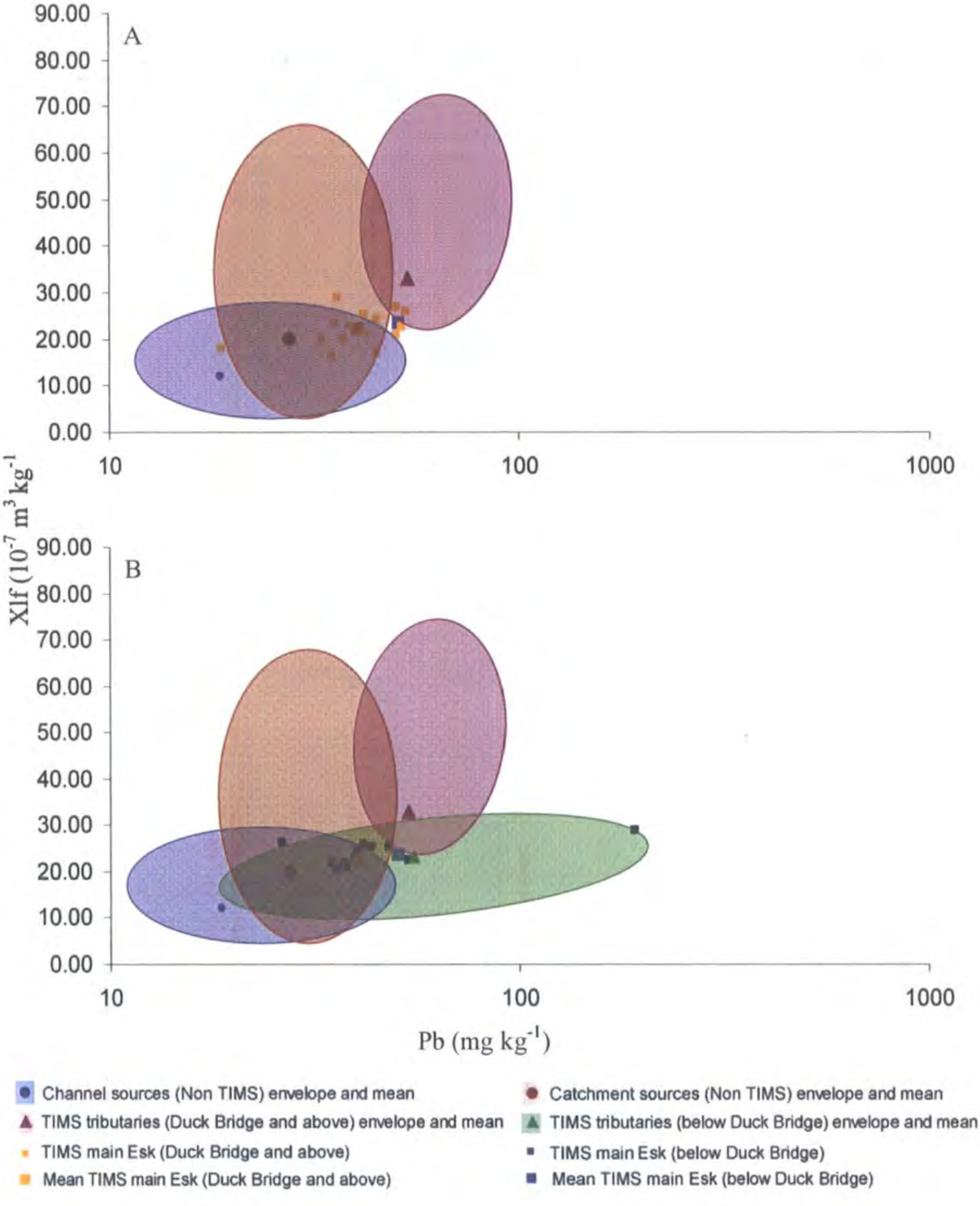


Figure 7.11: Comparison of Pb concentrations and Xlf values for: A) TIMS main Esk (above Duck Bridge); and B) TIMS main Esk below Lealholm, with mean Pb and Xlf concentrations for TIMS tributaries (above and below Duck Bridge) and channel and catchment (Non-TIMS) samples

Thus, combining magnetic properties and metal concentrations highlights the potential of using a composite of fine sediment characteristics to identify dominant sediment sources. Moreover, further evidence is provided supporting hypotheses of dominant sediment source areas inferred from the field mapping. However, limiting these findings is that only two sediment properties are used. To provide more definite source contributions and locations a larger number of parameters, such as additional magnetic properties (e.g. SIRM (IRM at 0.8 T) (Walling *et al.*, 1999b); or other properties such as fallout radionuclides (e.g. 136 (^{137}Cs), excess lead 210 (^{210}Pb) and beryllium – 7 (^{7}Be) (Peart and Walling, 1986; Olley *el al.*, 1993) could be used.

7.3 Chapter summary

These results highlight the limitations and problems inherent in identifying sediment source provenance using physical and chemical properties of suspended sediment and associated sediment source material. Firstly, the channel and catchment source samples (Non TIMS) and the TIMS tributaries and main Esk samples were not distinctive enough to allow suspended sediment samples to be adequately discriminated. In addition, the variability within the source group properties was too large for suspended sediment properties to be compared accurately (Small *et al.*, 2002). There was also a large amount of variability in the suspended TIMS sediment material as a result of grouping samples that had been collected over a six month period in varying storm and flow conditions. This high within-group variability relative to low between-group variability therefore greatly weakened the discriminating power of source groups (Collins *et al.*, 1997a; Rowan *et al.*, 2000).

There is still some uncertainty surrounding the discriminating power of the different parameters. This case study was limited in that only metal concentrations and magnetic susceptibility parameters were suitable to adequately identify dominant source areas. Issues associated with the use of 'unmixing' models were also highlighted in that it was not numerically possible to 'unmix' the suspended sediment properties from that of the source samples due to the large overlap found between source and suspended material (Figure 7.8, 7.11 and 7.12) (Walden *et al.*, 1997). A final factor, also limiting identification of the dominant sediment sources was that the spatial groupings were based on observations of dominant sources made during the channel reconnaissance survey, rather than on spatial distributions of geology and soil, which could potentially have large controls governing the spatial variability of sediment sources. These limitations could be minimised by collecting more source samples which provide better representations of the dominant source areas; hence allowing better discriminations of sediment source areas to be made in the Esk catchment.

Despite these limitations, comparison of measured properties of source and suspended material characteristics (e.g. magnetic susceptibility and metal concentrations) provides qualitative evidence that further supports the two hypothesises on dominant source locations in the Esk: Firstly, that dominant sediment source contributing to the high sediment fluxes near Danby is as a result local bank collapse: Secondly, that high sediment fluxes near Egton Bridge are predominantly sourced by wider catchment locations as a result of the high yielding tributaries that drain into the lower Esk (e.g. Great Fryup Beck, Glaisdale Beck and Butter). Furthermore, this chapter shows good potential for the development of quantitative 'unmixing' models using magnetic suspetibility and metal concentration sediment properties.

Chapter Eight: DISCUSSION

8.1 Overview

This purpose of this chapter is to combine the spatial and temporal patterns and processes of fine sediment transfer (Chapter 5; Research objective 1 & 2), mapped channel and catchment characteristics (Chapter 6; Research objective 3) and inferred dominant sediment sources (Chapter 7; Research objective 4) to produce a schematic sediment budget for the Esk catchment. This will not only confirm the 'hotspots' in fine sediment flux, but also identify the dominant locations of fine sediment transfers, storage, and sources contributing to these 'hotspots'. In addition, catchment controls and processes governing these high fine sediment fluxes will be determined (Section 8.2).

This schematic sediment budget will then be compared to the main locations and habitat requirements of the critical species in the Esk catchment (spawning salmonid and freshwater pearl mussels) (Section 8.3) in order to identify the link between high fine sediment transfers and declining spawning salmonid and pearl mussel populations in the Esk catchment. Based on the dominant locations of these critical species and the schematic sediment budget for the Esk catchment, a suitable catchment scale management strategy can be devised (Section 8.4). This will take into consideration the location of high areas of fine sediment flux in relation to the critical species, but also uses the detailed catalogue of catchment characteristics to suggest suitable, catchment management options and changes to land use practices (Research objective 5).

The implications of these findings in terms of their contribution to spatial and temporal patterns of fine sediment flux research, creating reconnaissance fine sediment surveys (with particular reference to the Babtie Root and Brown 'Catchment Fluvial Geomorphological Audit of the River Esk Catchment' (2004)) and creating catchment scale management plans in British Upland catchment, is evaluated (Section 8.5).

8.2 Synthesis of results

The first four research objectives were to identify spatial and temporal patterns in sediment transfer to infer 'hotspots' in fine sediment flux; to create a database of mapped channel and catchment characteristics and to identify dominant sediment sources in the Esk catchment (Section 1.1). This was achieved using the material retained in the spatially deployed TIMS samplers, which were emptied seven times over the six month monitoring period, in combination with a detailed reconnaissance survey of the River Esk catchment. In accomplishing these four research objectives, a vast wealth of information on significant areas and processes of fine sediment erosion, transport and deposition was obtained. To assimilate this data into a more digestible format, it was combined and displayed as a schematic sediment budget, highlighting the significant areas of sediment supply, transfer and storage in the Esk catchments.

8.2.1 Schematic sediment budget

In order to create a schematic sediment budget the wealth of collected data was firstly grouped according to spatial similarities;

1. Headwater tributaries (Commondale Beck, Baysdale Beck and Tower Beck);
2. Main Esk sampling sites, Duck Bridge and above (Six Arch Bridge, Danby and Duck Bridge);
3. Main Esk sampling sites, Lealholm and below (Lealholm, Glaisdale, Egton Bridge and Grosmont);
4. Great Fryup Beck;
5. Glaisdale Beck and Butter Beck
6. Murk Esk

Each measurable variable (e.g. weighted sediment flux, bank height, erosion extent) was categorized as high; medium; or low (relative to the data collected for the other TIMS sampling sites). These are summarised in Table 8.1 with the other mapped variables (e.g. bank material, erosion type, geology and topography). Colours have also been used to indicate the extent to which the presence of each category in each variable contributes to: low (blue); medium (orange); high (red); or very high (maroon) sediment fluxes (Table 8.1).

Using the combination of data in Table 8.1, reaches were then categorised as either low, medium or high in terms of their ability to transfer fine sediment, based on the assumption that fine sediment transfers were highest where the sediment fluxes were largest and channel gradients steepest. Similarly, zones of high and medium sediment storage were created where sediment fluxes were highest and where channel gradients were lowest (Table 8.1). Additionally, dominant supply areas in the catchmemt were estimated based on both the mapped channel (e.g. extent of bank erosion and bank material) and catchment characteristics (e.g. land use, hillslope and geology) in combination with the inferred sediment source areas. These estimated areas of fine sediment supply, transfer and storage were then transferred to a River Esk map, using different colours to represent the dominant locations of fine sediment supply, transfer, storage (Figure 8.1).

Figure 8.1 highlights three potentially problematic areas in the River Esk in terms of the amount of sediment being supplied, transferred and deposited to these locations (Danby to Duck Bridge (yellow) (Section 8.2.2)); (Glaisdale to Grosmont (dark blue) (Section 8.2.3)); Lealholm (green) (Section 8.2.3)). Again using this detailed spatial database, inferences can be made as to the dominant sediment input mechanisms and natural and anthropogenic causes governing high rates of sedimentation in these three areas (summarised in the coloured boxes in Figure 8.1).

8.2.2 Danby to Duck Bridge

The dominant process contributing to the high sediment loads in the section of the main Esk between Danby to Duck Bridge, are geotechnical failures of the local channel banks. This is a result of the banks being predominantly made up of coarse, sandy alluvium, which is poorly consolidated. This allows the bed and base of the banks to be easily scoured by fluvial activity; which increases the bank angle and height bringing about gravitational failure of the intact bank (Thorne, 1982).

	Weighted sediment flux (g d^{-1})	Bank height (m)	Bank material	Veg cover (%)	Vegetation type	Erosion extent	Vulnerability to erosion	Erosion type	Bank management	Catchment inputs	Land use in riparian zone	Slope (%)	Geology	Sediment source
Headwater tributaries	Low < 3	Low <1	Fines/ sand	Medium <50%	Grass	High	-	Fluvial	Poor in areas	Medium	Pasture	Medium	Mud, silt sand stone	-
Main Esk (Duck Bridge & above)	High >30	High >4	Sand	Low <30%	Bare/ grass	Very high	Very high	Geotech -nical	Poor	Medium	Pasture	Low	Some sandy alluvi- um	Channel banks
Main Esk (Lealhom & below)	V High >60	Low <1	Boulder	High <70%	Wood	Low	-	Fluvial	Not as much required	Low	Woods	Low	Sandy alluvi- um	Catchm - ents
Danby & Great Fryup Beck	Medium <15	Medium <2	Sand	Medium <50%	Bare/ grass	High	High	Fluvial	Poor	High	Pasture	High	Some boulder clay	Catchm - ent/ channel banks
Glaisdale & Butter Beck	High >30	Medium <2	Bedrock/ boulder	High <70%	Wood	Low	-	Fluvial	Not as much required	High	Woods	High	Boulder clay	Catchm -ent
Murk Esk	Medium <15	Medium <3	Boulder	High <70%	Wood/ grass	Low	-	Fluvial	Not as much required	Low	Woods	High	Boulder clay	-

Table 8.1: Synthesis of spatial and temporal sediment fluxes; channel and catchment characteristics; and inferred sediment source areas (categories that contribute to: low (blue); medium (orange); high (red); or very high (maroon) sediment fluxes are also indicated)

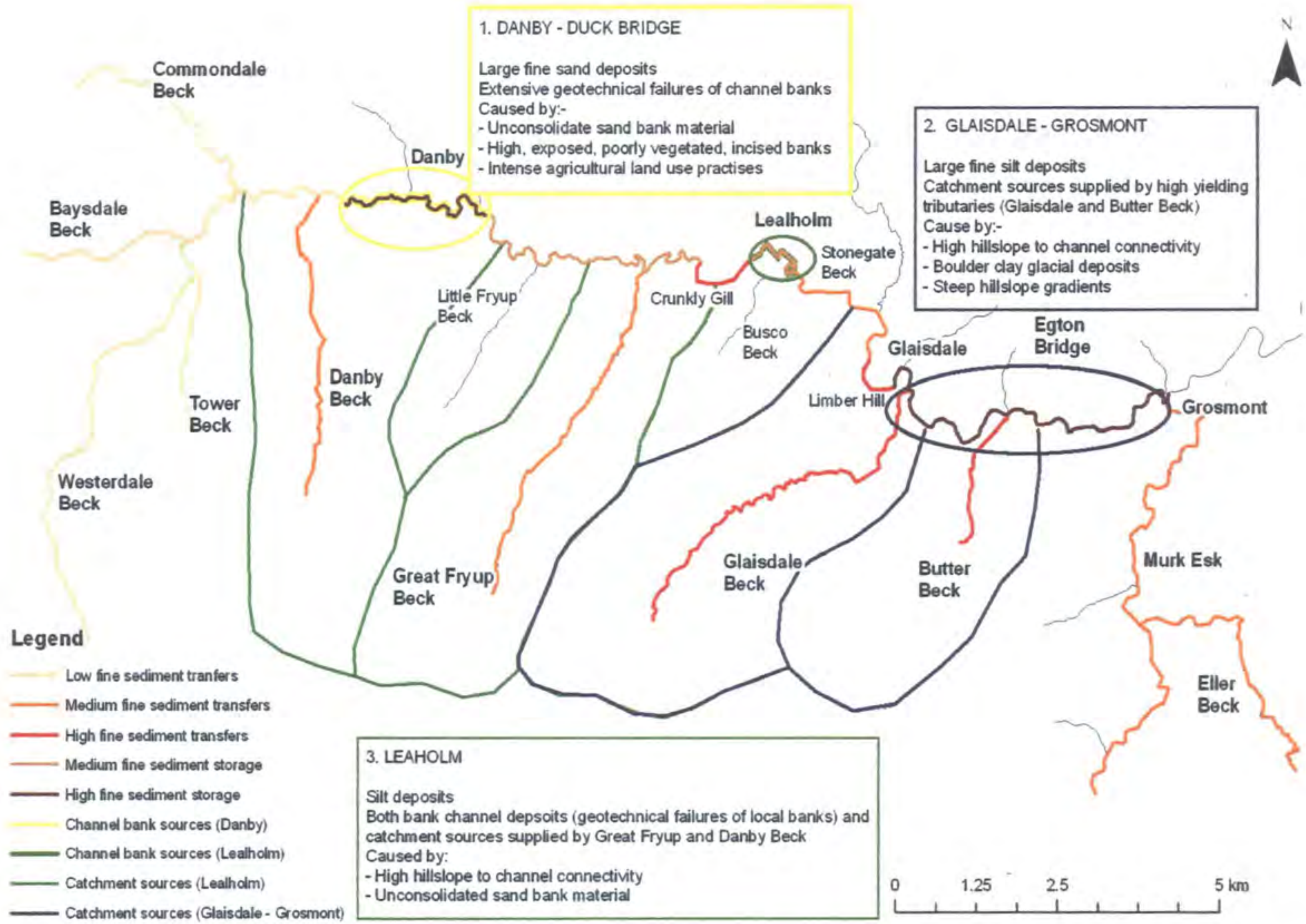


Figure 8.1: Schematic sediment budget of the River Esk catchment indicating locations, mechanisms and dominant sources of fine sediment transfer

The extent of these geotechnical failures depends largely on the nature and density of the vegetation cover on the banks, which was low at Danby. Although the relationship between bank erosion and vegetation is complex, vegetation affects erosion, bank stability, bank accretion and bank stabilization (Bull, 1997). Erosion by flow is affected by vegetation retarding the near-bank flow, damping the turbulence and decreasing the effectiveness of fluvial entrainment. Due to the binding affect of the roots, vegetation also reduces erodibility by resisting tension and increasing cohesion. In addition, vegetated banks are better drained and drier, reducing the impact of moisture and loosening processes, which are precursors to the removal of material. This is particularly important in terms of weathering processes, such as freeze thaw, which heave apart soil units, reducing its strength and stability; and consequently increasing the likelihood of failure (Thorne, 1982).

Agricultural practices in the adjacent riparian zone further exacerbate the extent of bank erosion at Danby. For example, animal poaching and farm tracks were observed to be particularly common here. This increases the amount of sediment disturbance and hence the amount of material transported and deposited into the river channel (Walling *et al.*, 2002). More importantly, fences to exclude livestock from the river edge and structures aimed at reinforcing the banks, such as walls, were identified as being poorly maintained in this section of the Esk. Some of these structures had fallen into the channel during previous high flow events (Figure 6.14); ironically causing higher sediment inputs from the detached and newly exposed bank material than if the banks had to been left untouched. Moreover, where these structures had collapsed into the channel, large amounts of material had built up behind them (Figure 6.5). This mass of material has the adverse affect of clogging and suffocating bottom dwelling aquatic species (Wood and Armitage, 1997), which is subsequently transported downstream in a large flush during high flow events.

8.2.3 Glaisdale to Grosmont

A second problematic stretch of the Esk is from Glaisdale to Grosmont (Figure 8.1). In contrast to Danby, it was the tributaries Butter Beck and Glaisdale Beck that were thought to be the principal suppliers contributing to the high sediment fluxes. Given the high degree of hillslope to channel connectivity associated with these tributaries (Figure 6.17), it was thought that these high sediment yields were predominantly sourced from the sub-catchments. A dominant control governing the high suspended sediment yields in these tributaries could be the presence of the boulder clay drift geology in the sub-catchments, (Figure 6.22). Glacial deposits, such as boulder clays, are by nature softer and more easily eroded than bedrock. Moreover, boulder clay is relatively impermeable and is susceptible to surface sealing allowing little water to be stored beneath the surface, so when rainfall intensity exceeds the surface infiltration rate during storms, surface runoff is generated at a rapid rate (Parsons and Abrahams, 1992). This, in combination with steep gradients of the hillslopes in these sub-catchments (Figure 6.21), and the affect of raindrop impact in detaching and preparing surface material for transport, means that in large precipitation events considerable amounts of fine sediment are mobilized and transported to the Esk. This fine sediment is then transported to the Esk river system via overland flow in the form of sheet erosion, rilling and gullying (Bridge, 2003). Once in the river network (given the finer particle size associated with boulder clay), this material is held in suspension and transported the length of these tributaries until the gentler gradient in the main Esk between Glaisdale and Egton Bridge, where as a result of the rapid gradient change, the velocity and carrying capacity of the flow is reduced and the sediment is deposited in large quantities on the bed (Knighton, 1998).

Substantial tree cover, although usually a precursor of stable soils and low erosion rates, could actually be enhancing the amount of catchment sediment inputs into Glaisdale Beck and Butter Beck. Firstly, owing to the dense forestry in the steeper sections of these sub-catchment, little light is emitted through the canopy layer and subsequently large sections of the valley floor are sparsely vegetated. These exposed surfaces are more susceptible to overland sheet erosion. Dead vegetation can also increase erosion as relic roots and root holes provide preferential pathways for seepage that can lead to piping; offering further explanations as to the large amount of sediment transferred from these sub-catchment during storms (Thorne, 1982). In addition, management has further exacerbated the observed suspended sediment yields in Butter Beck. In 2001, large woody debris was dredged and removed from Butter Beck. The aim of this was to increase sea trout stocks by giving them more habitat space. Removing woody debris from a natural stream causes the local water velocity to increase (Macdonald and Keller, 1987). Consequently, large amounts of material are flushed through Butter Beck with each high flow event; providing further rationale as to the extremely high sediment fluxes found given its small catchment area.

8.2.4 Lealholm

The schematic sediment budget (Figure 8.1) highlights Lealholm as having a significant amount of sediment storage, although not to the same extent of Danby, Glasidale and Grosmont. The steep boulder bed channel gradients and faster flow at Crunkly Gill, upstream of Lealholm, are precursors of increased sediment transport in this section (Figure 8.1). When flow enters the gentler, wider section of the Esk near Leaholm, the velocity and carrying capacity of the flow is greatly reduced; thus large amounts of sediment is deposited on the bed, contributing to the high observed sediment loads at this location.

The supply areas and processes of sediment input are more complex, but results of the channel and catchment mapping imply the sediment is supplied from a mixture of local channel bank, as a result of geotechnical failures evident at Leaholm (Figure 6.12); as well as sediment inputs from the sub-catchments of Great Fryup Beck and Danby Beck (Figure 5.3). As with Butter Beck and Glaisdale Beck, Great Fryup Beck and Danby Beck have a steep topography (Figure 6.21), high hillslope to channel connectivity (Figure 6.17) and the lower section of Great Fryup Beck is also underlain by a boulder clay drift geology (Figure 6.22). The land use in these tributaries is characterised by intensive agricultural practices and extensive amounts of poaching and farm assess tracks and fords were observed in its riparian zone (Section 6.4). This helps explain the high sediment yields supplied by these tributaries. Little Fryup Beck and Busco Beck (Figure 8.1), which were not monitored by TIMS but were included in the point 'gulp' samples, have similar catchment characteristics and were identified as having extremely high suspended sediment concentrations (Figure 5.6). Therefore it is likely that sediment supplied by these tributaries also contributes to the high sediment fluxes at Lealholm; hence more detailed investigations of the sediment dynamics and channel characteristics of these smaller tributaries should be a future priority.

8.2.5 Summary of results

To summarise, the schematic sediment budget (Figure 8.1) effectively combined the spatial and temporal sediment flux data with the mapped catchment characteristics, highlighting three potentially problematic locations in terms of suspended sediment transfer and supply in the main Esk. These included:

1) Danby to Duck Bridge where large sediment loads dominated as a results of extensive local channel bank failures caused by large amounts of poorly cohesive sand bank material which were subjective agricultural impacts, such as poaching and farm fords. Poor maintenance of riparian fences further weakened and exacerbated these bank failures.
2) Glaisdale to Grosmont where very high sediment loads were contributed to by the extremely high yielding tributaries of Butter Beck and Glaisdale Beck. These high fluxes were thought to be caused by catchment sources as a result of their sub-catchments being characterised by steep, wooded topographies underlain by boulder clay. The high yields in Butter Beck were considered to be further aggravated as a result of management practices such as channel dredging.
3) Lealholm was identified as a significant fine sediment storage reach, as a result of both geotechnical failures of unstable, poorly maintained banks influenced by anthropogenic impacts such as poaching and farm access roads; and the addition of catchment sediment sources supplied by Great Fryup Beck and Danby Beck.

8.3 Implications for critical species

It is commonly accepted that high suspended solid loads and sedimentation in certain sections of a river system can have a deleterious effects on riverine habitats (Davies-Colley *et al.* 1992; Graham 1990; Reiser, 1998). With particular reference to the River Esk catchment, spawning salmonids and freshwater pearl mussel habitats have been documented to be under rapid decline, thought to be associated with the increase in suspended sediment yields in response to the more intensive land use management (agricultural and forestry) in recent years (EA, 2004). Using the schematic sediment budget (Figure 8.1) fine sediment transfer can be examined in relation to dominant locations of both the spawning salmonid and fresh water pearl mussel habitats (Figure 8.2).

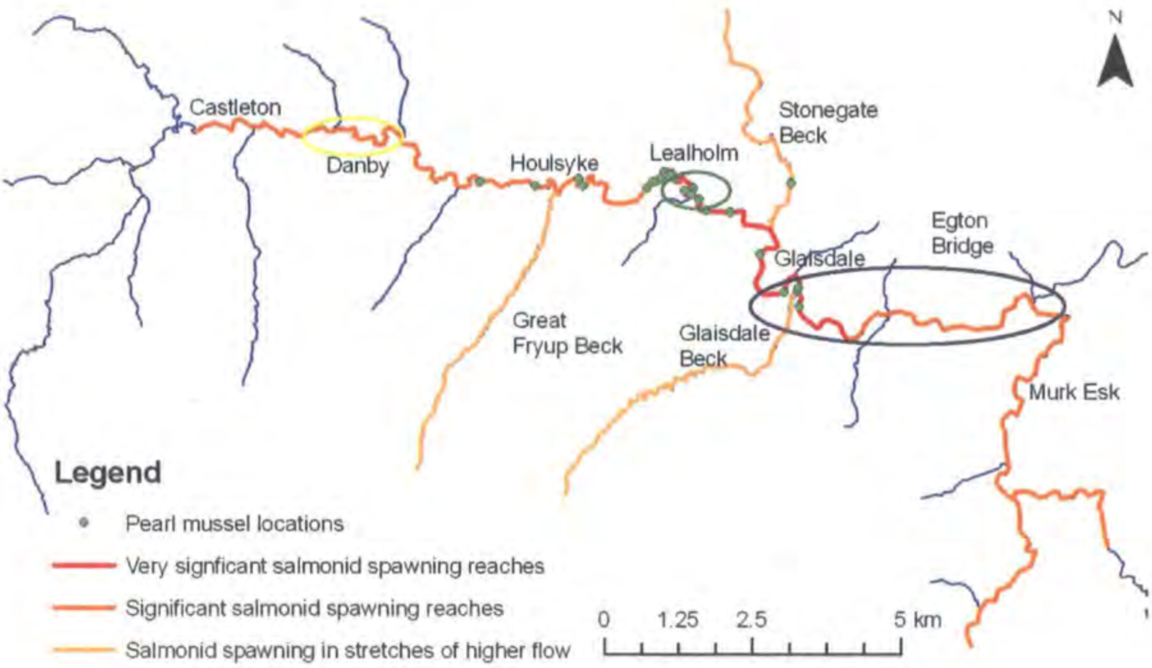


Figure 8.2: Location of critical species in relation to dominant areas of fine sediment transfer and storage on the River Esk

Given the complex nature of salmonid habitat requirements, which is highly variable with life stage (eggs, alevin, parr smolt and salmon), specific salmonid species and seasonality (Reiser, 1998), for simplicity it is the conditions of salmon spawning environments and the affect of high fine sediment amounts, that have been focused on.

It has been suggested that favourable conditions for salmon spawning are where river gradients are less than 3%, velocity between 0.25 – 0.9 m s^{-1}, a water depth between 0.17–0.76 m, where a gravel of suitable coarseness is present and interstices are kept clean by up-welling flow (Hendry and Cragg-Hine, 1997). The composition and mean grain size of spawning gravels varies markedly, but typically consists of a mix of cobbles (22-256 mm), pebbles (2-22 mm) and fine material (< 2 mm) (Cowx and Fraser, 2000). For successful incubation of the ova and subsequent emergence of the fry, it is essential that there is an adequate flow of water though the gravel. It is therefore important that the content of fines (< 2 mm) should be low; large inputs of which, associated with bank failures and high flow periods, clog gravel matrices, reduce permeability of spawning gravels and reduce oxygen supply to ova, resulting in high egg mortalities (Soulsby *et al.*, 2001). Hence the large fine sediment loads observed at Danby, Glaisdale to Egton and Lealholm, also identified as significant salmonid spawning stretches (Figure 8.2), could be the reason behind the recent decline of salmon and trout populations in the Esk.

Pearl mussel locations are found on the River Esk between Houskye and Glaisdale, but are particularly dominant near Lealholm (Figure 8.2), identified as a zone of sedimentation (Figure 8.1). Again, although still widely debated, it is believed that the intrusion of fine sediment is one of the main factors causing the recent reductions in peal mussel numbers (Hastie *et al.,* 2000). More specifically to the Esk, the correlation between locations of high sediment fluxes and pearl mussel habitats, particularly at Glaisdale and Lealholm, could therefore be significantly contributing to their recent rapid decline. Additionally, pearl mussels have been sighted on Stonegate Beck (Figure 8.2), which was unmonitored by a TIMS sampler and unmapped during the catchment reconnaissance survey; so represents a tributary for future research to further elucidate the link between pearl mussel decline and high rates of fine sediment transfer.

However, it is not yet known the specific particle size of the fine sediment thought to be causing the detrimental impacts to aquatic habitats (Hendry and Cragg-Hine, 1997). This is an especially important consideration in the Esk, given the variation in dominant particle size collected at the sediment 'hotspot' locations, ranging from fine sands at Danby to fine silts at Egton Bridge (Figure 7.3; Table 8.1). Moreover, a significant number of factors, other than fine sediment intrusion, have also been attributed to the recent decline in salmonid numbers and pearl mussels habitats, such as over fishing, industrial pollution and eutrophication of rivers and increased urbanisation near river catchments (Cosgrove *et al.*, 2000). Therefore it is unlikely that the recent decline in the critical species is a result of excessive fine sediment inputs alone, but due to multitude of different factors; hence, alleviating high sedimentation levels using target management strategies, may have only a negligible affect on the declining salmonid and pearl mussel habitats.

In summary, despite these uncertainties, strong correlations between the dominant locations in fine sediment transfer and storage (Danby, Glaisdale to Grosmont and Lealholm) can be linked to the dominant salmonid spawning stretches and pearl mussel habitat locations. The high rates of sedimentation in these areas may therefore be attributed to their recent decline. This highlights the management need to alleviate these high levels of fine sediment in these areas; particularly at Lealholm, which although had lower sediment yields and fluxes, is a very significant salmonid spawning and pearl mussel site in the Esk catchment

8.4 Management strategies

Although land use management for much of the Esk catchment is of a high quality; based on the sediment budget (Figure 8.1), the locations of the critical species (Figure 8.2) and catchment mapping (Chapter 6), a catchment scale management strategy for alleviating rates of fine sediment transfer and sedimentation, especially at the 'hotspot' locations, can be proposed (Figure 8.3) (Research objective 5). In preference of 'softer', practical solutions to problems of high suspended sediment transfers, this management strategy adopts simple, yet effective changes in farm land use management which not only avoids the most disruption to the catchment, but is easy to implement and maintain without incurring major costs (Hicks, 1995; Palanisami *et al.*, 2002).

The management strategy highlights three critical areas in the Esk catchment as potentially causing significant inputs of fine sediment (Figure 8.3) (estimated areas that required management are summarised in Table 8.2):

1. Channel banks (of most of the upper section of the Esk and some sections of dominant tributaries);
2. Catchment management of the steep sloping pasture fields in the sub-catchments of Danby Beck and Great Fryup Beck;
3. Catchment management of the steep woodland draining the lower section of Glaisdale Beck and Butter Beck.

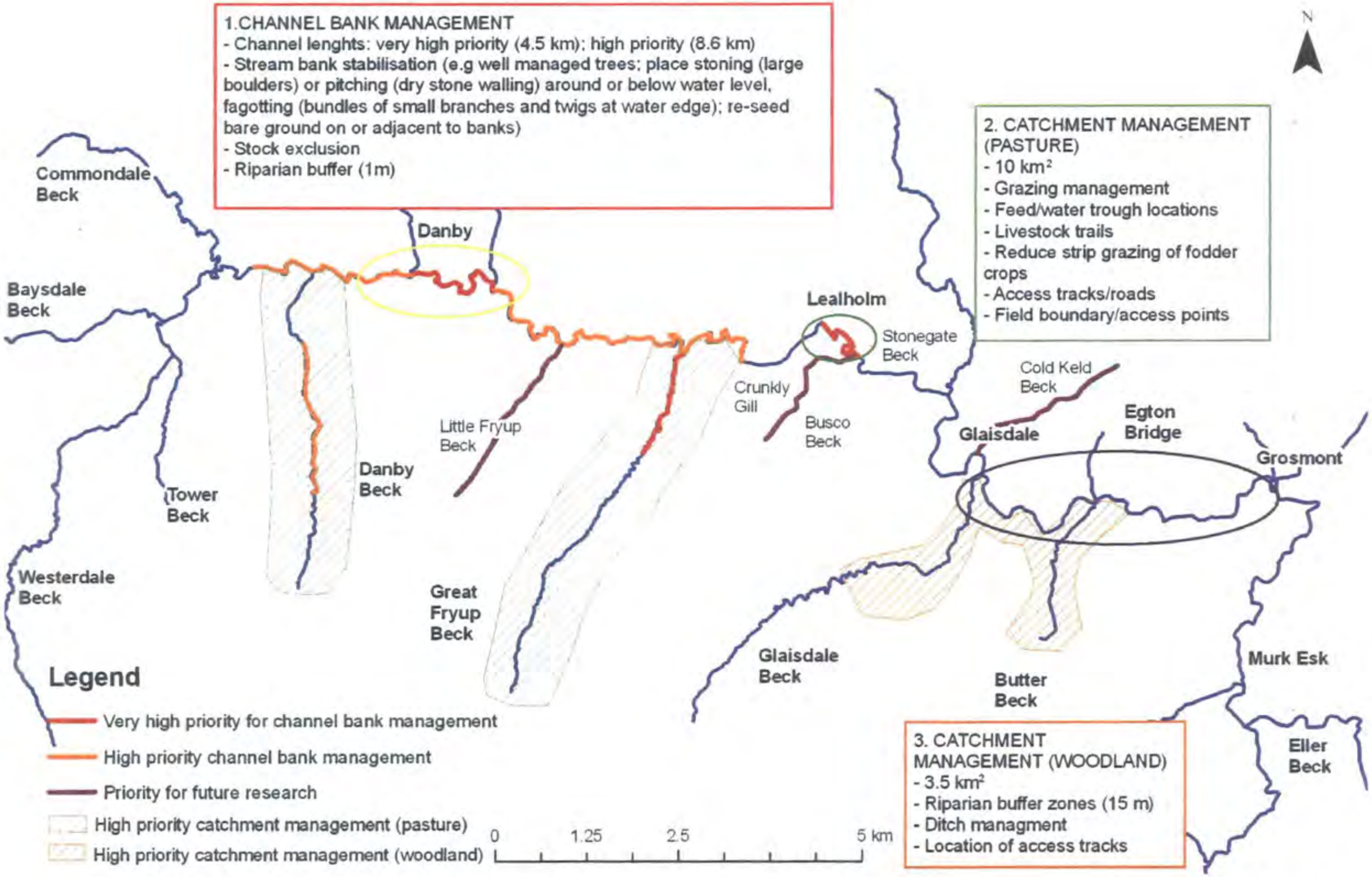


Figure 8.3 Catchment scale management strategy for the River Esk catchment indicating high priority areas in need of channel bank and catchment (pasture and woodland) management

Table 8.2: Estimated lengths of channels (km) and areas of the catchment (km^2) that require management in the Esk catchment

Type of catchment management required	Location in the Esk catchment	Length of channel (km)/area of catchment (km^2) requiring management
1. Channel banks		
- Very high priority	River Esk near Danby Moors Centre	1.8
	Lower section of Great Fryup Beck	1.6
	River Esk near Lealholm	1.1
- High priority	River Esk above Danby	2.6
	River Esk below Danby	5.5
	Middle section of Danby Beck	2.0
	TOTAL	**14.6 km**
2. Catchment management		
- Pasture	Danby Beck sub-catchment	4.9
	Great Fryup Beck sub-catchment	6.0
	TOTAL	**10.9 km^2**
3. Catchment management		
- Woodland	Glaisdale Beck sub-catchment	2.0
	Butter Beck sub-catchment	1.5
	TOTAL	**3.5 km^2**

8.4.1 Channel bank management

Reaches of the River Esk and dominant tributaries that were of highest channel bank management priority were identified (Figure 8.3). This was based on the assumption that the sections of the bank composed of sand; had the highest erosion rates; were characterised by geotechnical failures; had the highest fine sediments fluxes; and were the most significant reaches in terms of the critical species locations, represented the greatest need of riparian bank management. Consequently, the banks of the main Esk at Danby (1.8 km), Lealholm (1.1 km) and the lower sections of Great Fryup Beck (1.6 km) were highlighted as the most critical. The banks for the rest of the section of the main Esk above Leaholm (8.1 km) and sections of Danby Beck (2 km) were also highlighted as requiring management.

Livestock exclusion via riparian fencing, except for small watering areas where required, have been proven to decrease the amount of sediment inputs associated with animal poaching at the waters edge. Once in place, without disturbances from grazing livestock, bare sections of the bank natural revegetate, hence strengthening and decreasing its susceptibility to bank failure (Hilton *et al.*, 2003). Increased bank vegetation cover will trap residual sediment runoff from adjacent pastures and will decrease the amount of organic pollutants entering the river. However, in relation to the Esk catchment, it is not the installation of riparian fences that are an issue; rather it is the maintenance of these structures. This is especially so after large storms since for many sections of the banks, particularly in the smaller tributaries such as Great Fryup Beck and Danby Beck, riparian fences were found to be in poor condition and significantly contributing to fine sediment inputs.

In critical areas, such as at Danby, where the sections of banks are particularly vulnerable to erosion, the stream banks may need further stabilisation through measures such a critical tree planting, place stoning (large boulders) or pitching (dry stone walling at the toe of the banks) around or below the water level; fagotting with willow whips (bundles small branches and twigs laid near the waters edge and tied in place; or re-seeding the bare gound on or adjacent to banks) (Hilton *et al.*, 2003). The success of such measures depends on the size and extent of erosion and local bank conditions. For example at Danby, given the nature of the high, steeply inclined banks poorly suited to plant growth, planting would not be a viable option and associated disturbances of the bank is likely to cause more sediment inputs then if it had been left untouched. Moreover, although these are relatively simple options that can be undertaken by farmers themselves, some may be labour intensive and all require essential maintenance.

Farm fords and stream crossing were also identified as significantly weakening the banks in the Upper Esk. These inputs can be reduced with the provision of bridges, culverts and armoured fords. Although these must be kept to a minimum by combining their usage with both livestock and machinery purposes and only building them where absolutely necessary. However, this management option may be impractical in some of the larger sections of the Esk due to the high costs and disturbances incurred.

8.4.2 Catchment management of pasture fields

Significant sediment inputs associated with agricultural land use management practices were also identified as important in the River Esk catchment. Of particular concern are the intensively farmed, steeper sub-catchments draining Great Fryup Beck (6 km^2) and Danby Beck (4.9 km^2) (Figure 8.3). The sediment inputs associated with runoff from pasture fields can be minimised by making small changes to management practices. For example feed and water troughs, livestock movement, access tracks and roads and field boundary access points, can be relocated away from stream banks and erosion sensitive areas to hardened surfaces or on the top of slopes, less vulnerable to erosion (Hilton *et al.*, 2003). Changes can also be made to grazing management, such as livestock rotation between paddocks, avoidance of mob stocking during droughts, cold or wet weather (when the soil is most susceptible to erosion), and ensuring the maintenance of an all year round good residual ground cover (Hicks, 1995). These simple changes to the management of pasture fields not only have the advantage of decreasing the amount of erosion and hence sediment inputs to the river via overland flow, but also increases the productivity and recovery of the land. The success of these catchment management options on pasture fields depends on the maintenance and on going implementation of them.

8.4.3 Catchment management of the steep woodland

The steep woodland lining the lower section of Glaisdale Beck (2.0 km^2) and Butter Beck (1.5 km^2) was also highlighted as being important areas for targeted management strategies aimed at alleviating high sediment transfers (Figure 8.3). Here, the creation of riparian buffer zones, at least 20 metres in width, wider in areas of high soil erodibilty and steepness of slope, was identified as the most suitable management procedure. These buffer zones, once fully vegetated by naturally occurring vegetation, will reduce the rate of overland flow and encourage sedimentation by trapping suspended sediment solids; thus reducing the amount of sediment entering the tributaries. However, crucial to the operation of these filter strips is that they should be logically located to ensure that during heavy rainfall the force of the overland flow is not so great as to bypass the filtering effect of the vegetation or to re-entrained the previously captured material (Heathcote, 1998).

The success of these buffer zones also depends on the extent to which the land use changes in the pasture fields (Section 8.4.2) are implemented and should be used in combination with other land use management practices such as ditch management and the relocation and maintenance of access routes and footpaths away from erosion sensitive areas and river edges. However, because the extent and significance of the tile drains and subsurface flow channelling water and sediment to Butter Beck and Glaisdale Beck is unknown, there is some uncertainty surrounding the ability of these buffer zones reducing fine sediment inputs.

Lastly, with respect to the dredging of Butter Beck in 2001, which is thought to have created notable increases in sediment yields during storms, little can be done apart from continued monitoring of the sediment dynamics to assess whether in time sediment levels are declining.

8.5 Wider applications of research

8.5.1 Time integrated mass samplers – assessing spatial and temporal patterns of fine sediment flux

The spatial and temporal patterns of fine sediment transfer in the River Esk were measured using TIMS samplers, which once spatially deployed in the catchment, provided an indication of sediment flux at each sampling site. Since the design of these TIMS was relatively recent (Phillips *et al.*, 2000) and their application in fluvial research relatively limited (Russell *et al.*, 2000), this projects acts as a pilot study demonstrating the success of using such samplers to assess spatial and temporal fine sediment flux. Not only did the TIMS samplers allow a detailed assessment of the areas within the catchment most significant in terms of fine sediment transfer, but also allowed an application of the temporal influence of seasonal and high flow conditions on these spatial patterns. The TIMS samplers also had the advantage of collecting an *in situ* bulk sample, large enough for particle size, metal content, magnetic susceptibility and colour to be measured, allowing a detailed spatial database of fine sediment characteristics to be created. This was then be compared with similar properties of collected sediment source samples, highlighting the potential for using TIMS samplers in fingerprinting investigations to accurately identify dominant source contributions within a catchment (Russell *et al.*, 2000; Collins and Walling., 2004). By analysing the spatial pattern of calculated sediment flux and specific yields, this research highlight the potential of using TIMS samplers to increase the spatial resolution of fluvial sediment budgets at the reach and catchment scale; although absolute yield cannot be determined without knowing the efficiency of the sampler in collected accurate, representative suspended sediment samples, in addition with the flow history at each site.

8.5.2 Stream reconnaissance surveys

A potential framework for successfully identifying channel bank characteristics for geomorphically defined reaches on a catchment scale has been developed. The approach adopted here is similar to the reconnaissance survey of the 'Catchement Fluvial

Geomorphological Audit of the River Esk Catchment' commissioned by the Environment Agency and carried out by Babtie Brown and Root (2004). The main aim of this audit was to 'characterise geomorphological conditions within defined watercourses to inform a range of catchment management initiatives' (Babtie Brown and Root, 2004). In comparison to the reconnaissance survey of the Esk catchment presented in this report, a larger area, including the section of the catchment between Glaisdale to Clough Gill near Whitby, was surveyed. However, in the Babtie Brown and Root survey, the resolution of the individual reaches surveyed was poor (over 1 km in parts) and too coarse to allow for the variations in channel characteristics to be adequately mapped. Furthermore some of the significant sediment supplying tributaries were not mapped (e.g. Butter Beck) and most of the sites were only visited once, meaning in terms of the seasonal and storm controls and the geomorphological context, observations were extremely limited. Moreover, sediment supply and storage processes where lumped together; for example fluvial erosion, geotechnical failure, input from the catchment and hillslope supply were all classed as diffuse sediment sources, greatly limiting the utility of the survey. These limitations therefore made suitable site specific management strategies extremely difficult to devise accurately and effectively.

In contrast, the reconnaissance survey produced in this report has greater spatial resolution using shorter survey reaches, identified the individual processes contributing to sediment supply, transfer and storage, and had the advantage of being used in combination with the data collected from the TIMS samplers. This large database of information on the River Esk catchment augments the relatively small inventory of fine sediment flux characteristics in British Upland catchments; and can be used to produce a schematic sediment budget, identifying the dominant sediment inputs, transfer and storage (Figure 8.1).

8.5.3 Catchment management

Finally, this research project provides a framework in which suitable management initiatives for controlling fine sediment transfers can be identified and implemented (Figure 8.4). This allows an integrated catchment management approach which identifies the problematic fine sediment locations and produces remedies based on local catchment characteristics. If proven, this framework could be adopted and applied to other catchments in alleviating rates of high suspended sediment in association with recent changes to land use management practices. The framework is also a useful tool increasing the communication between the researchers, management authorities and the local communities.

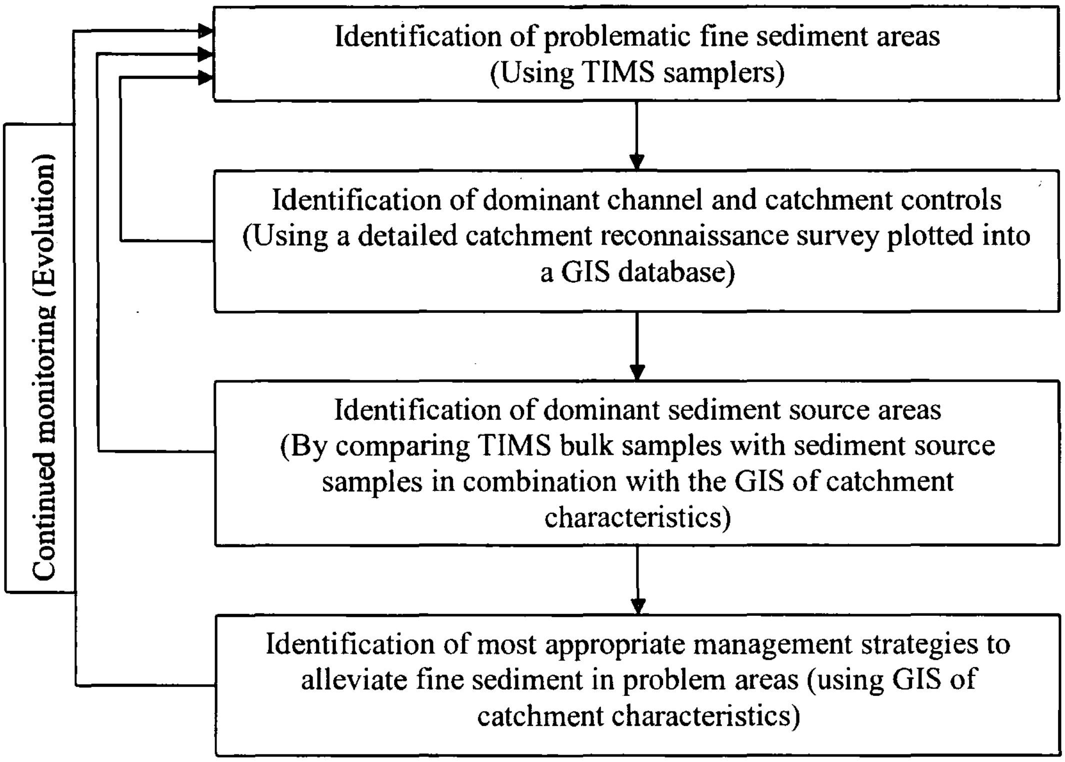


Figure 8.4: Possible catchment scale framework for alleviating and managing fine sediment

Chapter Nine: CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

9.1 Overview

The purpose of this chapter is to summarise the main conclusions of this research project. To assess the extent to which these conclusions are valid, the main limitations are also highlighted and areas for improvements and future research suggested.

9.2 Conclusions

The aim of this research was to assess the relationship between spatial variations in fine sediment supply and their dominant source areas in the River Esk catchment. In achieving this five research objectives were formulated (Section 1.3) and are used here to summarise the main conclusions:

1) to determine spatial variations in fine sediment transfer, identifying dominant reaches with high suspended sediment flux in the River Esk catchment;

Spatial patterns of fine sediment transfers were found to be highly variable; although two dominant 'hotspots' where identified as having the highest fine sediment flux in the River Esk catchment: 1) Danby to Duck Bridge: and 2) Glaisdale to Grosmont.

2) to determine the temporal influence of flow dynamics on spatial patterns of sediment transfer;

During high flow conditions large amounts of sediment were observed to be mobilised and transferred within the drainage network; especially between Glaisdale to Grosmont in the River Esk and in the tributaries Great Fryup Beck, Glaisdale Beck and Butter Beck. A strong relationship between fine sediment flux and peak stage was observed but this was highly variable and complex on a local scale. For example, at Danby poor correlations between sediment flux and peak stage were observed (R^2 = 0.18), yet a stronger relationship was found at Butter Beck (R^2 = 0.74). A weaker relationship was observed between total rainfall and fine sediment flux (R^2 = 0.49) which again was highly spatially variable with a poor relationship found at Danby (R^2 = 0.20), but a stronger correlation at Butter Beck (R^2 = 0.63).

> *3) to understand the links between spatial patterns of fine sediment flux with both channel and catchment scale characteristics, using channel mapping techniques to create a GIS database of catchment attributes;*

Local channel banks were identified as the dominant sediment source contributing to the high sediment fluxes near Danby given the high, sandy, poorly vegetated nature of the banks where extensive bank slumping dominated. Moreover, intensive agricultural practices, for example poorly maintained riparian fences and farm fords, also influenced the occurrence of these geotechnical failures. In contrast, wider catchment sources supplied by high yielding tributaries (Glaisdale Beck and Butter Beck) were inferred as the dominant sediment source contributing to the high sediment yields at Glaisdale to Grosmont; owing to the high hillslope to channel connectivity and the dominance of a soft boulder clay drift geology underlying the sub-catchments.

> *4) to identify the main sediment source areas in the catchment that supply the dominant zones of high suspended sediment flux;*

Comparisons of the particle size, sediment colour, magnetic susceptibility and metal content of the TIMS suspended sediment with possible sediment source samples provided qualitative evidence of the dominant sediment source locations inferred from the catchment mapping; particularly when magnetic susceptibility and metal content values were combined (Figure 7.11). Limitations in the application of 'unmixing' models for estimating source area contributions were also highlighted. For example the inherent within-group variability relative to low between-group variability caused the properties of the suspended sediment to overlap with that of the source groups. This made it numerically unfeasible to 'unmix' dominant sediment source contributions. However, the potential of using magnetic susceptibility and metal content in an 'unmixing' model to provide a quantitative assessment of dominant source areas in the Esk catchment was highlighted.

5) to inform effective management strategies to alleviate sedimentation in problem areas.

The schematic fine sediment budget (Figure 8.2) incorporated all the results (Research objective 1 – 4) to indicate the dominant fine sediment source, transfer and storage areas in the River Esk catchment. This highlighted the reaches of the River Esk from Danby to Duck Bridge, and from Glaisdale to Grosmont as being areas of high fine sediment storage. The tributaries Glaisdale Beck and Butter Beck, and the section of the main Esk near Crunkly Gill and Limber Hill were also highlighted as significant reaches in transferring fine sediment in the River Esk. Lealholm was identified as an important location in terms of fine sediment transfers due to its close proximity to the critical species affected by fine sedimentation. The channel banks above Lealholm; steep, intensively farmed pasture fields in Danby Beck and Great Fryup sub-catchments; and steep woodland in the lower section of Glaisdale Beck and Butter Beck sub-catchments, were identified as high priority areas for targeted catchment management. Suitable target initiatives, aimed at alleviating fine sediment transfer, included: riparian fencing; bank reinforcements; livestock rotation; and the creation of buffer zones.

9.3 Limitations, improvements and future research

9.3.1 TIMS samplers

TIMS can be criticised for a number of reasons: field efficiency is difficult to assess; they only sample from a small cross sectional area of the channel; changing stage may affect the local flow regime; and the inlet may become blocked by floating debris (Armstrong, 2005). Thus the sediment flux calculated from the mass of the bulk sample are prone to error; limiting the extent to which spatial patterns of fine sediment flux can be inferred. However this was minimised by weighting the sediment fluxes and yields by bankfull channel cross sectional area and catchment area; and keeping the sampling periods relatively short to decrease the amount of time the sampler could potentially be blocked. The efficiency of the samplers need further investigation using flume or field experiments.

Spatial patterns in fine sediment characteristics measured using the bulk samples are limited by the size selectivity of the sampler. For example, as the intake velocity is lower than that of the channel, coarser particles are less likely to enter the sampler. Once in the sampler, larger, heavier particles are preferentially deposited. Also, during high flow events the sampler may sample some of the bed load material rather than just the suspended load, and some of the fine particles will be carried nearer the surface, so not captured by the sampler. This adds uncertainty when assessing spatial patterns in particle size distribution and when comparing the chemical properties of the bulk sample with that of source samples.

However most of these uncertainties with the sampler design outlined above were determined from flume experiments and both Russell *el al.* (2000) and Phillips *et al.* (2000) report improved results can be expected in field conditions. To establish the extent to which the samplers collect representative samples, multiple TIMS samplers could be deployed in the same cross section and monitored over several sampling periods incorporating a range of flow conditions.

The sampler position within the channel has a large influence over the suspended sample collected. For example if located in the thalweg of the flow, where the velocity is highest, comparatively more sample will be collected. This will result in the sediment flux at this location being over estimated in comparison to other sections of the cross section. However this was minimised by installing all the samplers in the central, quickest flowing part of the channel cross section, at approximately 10 cm from the bed.

Not all samplers were installed at the same locations in each tributary. For example in tributaries such as Commondale Beck, Baysdale Beck and Westerdale Beck the samplers were deployed relatively far up the tributaries; whereas at Butter Beck, Glaisdale Beck and Great Fryup Beck, the samplers are located near the output to the Esk (Figure 4.1). Although unavoidable due to the inaccessibility of some of the tributaries, this could be a significant in controlling the spatial patterns of sediment dynamics observed since the larger channel dimension nearer the mouth of the tributary have higher capacities to transport suspended sediment; hence TIMS located at longer distances from the headwaters will retain comparatively larger bulk samples. The influence of distance deployed from the headwaters could be investigated further by locating multiple TIMS at equal distances down certain tributaries and comparing the results.

9.3.3 Length of monitoring period

One of the main limitations to this research project was the short six month monitoring period. This means that the conclusions made are specific to the study period and not necessarily indicative of fine sediment fluxes on a longer time scale. This was unavoidable given the fixed time frame of the project, but could be reduced in future by devising a research methodology over a longer time frame so to ascertain, with increased certainty, the influence of seasons and individual storm events on suspended sediment flux.

9.3.4 Spatial coverage

Although a large area of the Esk catchment was investigated, not every tributary was monitored with TIMS (e.g. Busco Beck, Little Fryup Beck and Cold Keld) and not every section of the catchment was mapped due to accessibility and logistic problems (e.g. top sections of some of the tributaries). Moreover, the catchment mapping carried out focused more on the riparian zone rather than the whole catchment. Consequently, there could have been sources, inputs and transfers of fine sediment unaccounted for, which could make the conclusion drawn from these spatial trends inaccurate. Although the storm 'gulp' samples minimised this uncertainty by providing a preliminary insight to sediment dynamics in some of the smaller, unmonitored tributaries. This uncertainty could be reducing by increasing the number of TIMS samplers deployed and by mapping a more extensive area in future research.

9.3.5 Sediment source identification

The source samples collected, with the aim of identifying dominant source areas, were limited by large within group and low between group variability, making their discriminatory powers weak. This meant dominant contributing sources could not be estimated using a quantitative fingerprinting methodology. In future, it is vital that a larger number of source samples are collected from areas that define the dominant sediment sources more accurately and that a larger number of measured properties are used to provide a wider composite of characteristics (Collins *et al.*, 1997b.

9.3.6 Bedload transport

This research project focused on the measurement of suspended sediment transfer, however with respect to aquatic habitats requirements, it is arguably the increased intrusion of fine bedload material, rather than suspended, that is more problematic (Reiser, 1998). In consideration of this, future research projects in the Esk catchment could measure both bedload transport (particularly sand waves and sheet), with the use of a spatially deployed portable bedload traps (e.g. Bunte, 2004) in addition with TIMS samplers. This would therefore achieve spatial patterns in both suspended sediment and bed load transport; the combination of which is relatively limited with in fluvial literature.

9.3.7 Representativeness of the study catchment

Lastly, given the unique glacial history and small catchment size of the River Esk, this research project can be criticized as being extremely site specific. This could limit the extent to which the collected data set can be extrapolated to other upland catchments; and hence the contribution of this research to the knowledge base of sediment dynamics in the UK British Uplands. The site specific nature of this project could be minimized in future by carrying out a similar research methodology in other upland catchments, such as in the Tees or Wear catchments. However, what this research project does successfully do, is contribute to the knowledge of Upland, predominantly rural catchment management studies and projects, especially those aimed to alleviate fine sediment inputs so to sustain economically important fisheries.

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